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VERIFICATION OF THE HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL USING FIELD DATA

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by

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16. ABSTRACT

This report describes a study conducted to verify the Hydrologic Evaluation of Landfill Performance (HELP) computer model using existing field data from a total of 20 landfill cells at 7 sites in the United States. Simulations using the HELP model were run to compare the predicted water balance with the measured water balance. Comparisons were made for runoff, evapotranspiration, lateral drainage to collection systems and percolation through liners. The report also presents a sensitivity analysis of the HELP model input parameters.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report describes a study conducted to verify the Hydrologic Evaluation of Landfill Performance (HELP) computer model using existing field data from a total of 20 landfill cells at 7 sites in the United States. Simulations using the HELP model were run to compare the predicted water balance with the measured water balance. Comparisons were made for runoff, evapotranspiration, lateral drainage to collection systems and percolation through liners. The report also presents a sensitivity analysis of the HELP model input parameters.

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ABSTRACT

Simulations of 20 landfill cells from seven sites were performed using the Hydrologic Evaluation of Landfill Performance (HELP) model. Results were compared with field data to verify the model and to identify shortcomings. Sites were located in California, Kentucky, New York, and Wisconsin and included a wide variety of climates and landfill designs. Landfill descriptions and soil properties were loosely defined, requiring much judgment in selecting model input values and allowing significant variance in the simulation results. The field measurements of the various water budget components varied greatly from cell to cell despite some having identical designs. Consequently, the precision of the verification effort is fairly low, but the study demonstrates that the HELP model is a useful tool for realistically estimating landfill water budgets. Simulation results generally fell within the range of field observations. The results indicated that two modifications in the HELP model may be warranted. Specifically, the computation of daily temperatures for estimating snowmelt and the estimation of unsaturated hydraulic conductivity for vertical drainage should be changed. Further study is needed for verification of lateral drainage and percolation when the infiltration rate is small.

A sensitivity analysis of the HELP model was performed to examine the effects of the major design parameters on components of the water budget for landfills. Hydraulic conductivity values for the topsoil, lateral drainage layers, and clay liners are the most important parameters in determining the water budget components. These parameters are particularly important in estimating the percolation through the landfill. Other design parameters tend to affect the apportionment among runoff, evapotranspiration, and lateral drainage from the cover. This information, along with the verification results, was used to evaluate RCRA landfill design guidance and regulation.

This report was submitted in partial fulfillment of Interagency Agreement DW96930236-01-1 between the U.S. Environmental Protection Agency and the U.S. Army Engineer Waterways Experiment Station. This report covers a period from October 1984 to September 1986, and work was completed as of September 1986.

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SECTION 1

EXECUTIVE SUMMARY

PURPOSE AND SCOPE

This study was performed to verify Version 1 of the Hydrologic Evaluation of Landfill Performance (HELP) model using existing field data. Mathematical simulations of 20 landfill cells at seven sites across the United States were made using the HELP model and were compared to measured field data. Measurements of leachate drainage were available from all 20 landfill cells, while data on runoff were available only from about half of the cells. Measurements of percolation were available only from one cell and no data on evapotranspiration were available. These landfills included a wide variety of conditions for which the HELP model was tested. The cells ranged in size from 0.04 to 24 acres and the simulation periods ranged from 2.5 to 8 years. This report summarizes the results of these simulations and evaluates the verification that has been achieved. In addition, the report presents a sensitivity analysis for the input parameters used in the HELP model and a review of landfill design regulation and guidance in light of the results of the verification studies and sensitivity analysis.

The HELP model was developed to help hazardous waste landfill designers and evaluators estimate the magnitudes of components of the water budget and the height of water-saturated soil above barrier soil layers (liners). This quasi-two-dimensional, deterministic computer-based water budget model performs a sequential daily analysis to determine runoff, evapotranspiration, percolation, and lateral drainage for the landfill (cap, waste cell, leachate collection system, and liner) and obtain estimates of daily, monthly, and annual water budgets (1,2). The model does not account for lateral inflow or surface runon.

The HELP model computes runoff by the Soil Conservation Service (SCS) runoff curve number method (3). Percolation is computed by Darcy's law, modified for unsaturated flow (1). Lateral flow is computed by a linearization of the Boussinesq equation, and evapotranspiration is determined by a method developed by Ritchie (4). The vertical percolation and evapotranspiration components of the HELP model originated with the Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (5). The development presented here, however, reflects a significant advance beyond the CREAMS model in both of these areas.

In the course of the development of any model, provisions should be taken to verify that the model accurately represents reality. Laboratory tests have been performed to verify the lateral drainage portion of the HELP model, but prior to this study the other portions of the model had only been calibrated and not verified. This report presents the results of efforts to verify the model using existing data collected at landfills, test cells and lysimeters.

This study consists of three parts. The main part is an attempt to verify the model using existing data. The purpose of this part was to assess the adequacy of the model to simulate reality and to validate the use of the model to evaluate designs (generally with minimum information). The second part of this study is a sensitivity analysis of the principal input parameters used in the HELP model. The purpose of this part was to determine which parameters need to be well-defined and what are the likely effects of a change in the value of a parameter. This analysis also provided much insight for interpreting and explaining the verification results. The third part of the study consists of an evaluation of the technical guidance developed to support the regulations regarding design and operation of a landfill. The purpose of this part was to examine the results of the laboratory and field verification studies and the sensitivity analysis to determine whether the technical guidance was practicable and achieved its objectives (particularly that of minimizing potential percolation through the liner at the base of the landfill) in the best practicable manner.

FIELD VERIFICATION

Comparisons were performed between simulations and measured field data for seven sites:

(1) University of Wisconsin-Madison. From 1970 to 1977, eight large lysimeter cells filled with either shredded or unprocessed refuse were monitored for surface runoff and leachate production. The general purpose of the study was to determine the effect on landfill performance of shredding the refuse prior to placement and covering the refuse with a soil layer.

(2) Sonoma County, CA. A solid waste stabilization project was sponsored by the U.S. Environmental Protection Agency and Sonoma County, California from 1971 to 1974. The purpose of the project was to investigate the stabilization of solid waste in five municipal sanitary landfill test cells by analyzing leachate, gas, temperature, and settlement parameters and to determine the effect on solid waste stabilization of applying excess water, septic tank pumpings, and recycled leachate. Leachate production was measured for all five cells and runoff was measured from three of the cells.

(3) Boone County, KY. Two field-scale test cells and three small-scale cells were studied from 1971 to 1980 in Boone County, Kentucky under the sponsorship of the U. S. Environmental Protection Agency. The study objectives were to evaluate the amount and characteristics of leachate, the composition of gases, the temperature conditions, the settlement of the cells, the clay liner efficiency, and to compare the behavior between the field-scale and small-scale cells. The data collected from one of the field-scale cells was used in this study.

(4-6) Brown, Eau Claire, and Marathon Counties, WI. The State of Wisconsin Bureau of Solid Waste Management has reported on the geologic setting, major design features, construction experience, leachate production and operational performance of these three large landfills in Wisconsin. These landfills were started between 1976 and 1980; however, none of these landfills has yet been completely filled and capped so that each data set reported thus far represents the conditions of a continuously expanding landfill. For example, at any given time, the cover could range from the daily cover of a 6-inch-thick blanket of sand or silty clay to a final cover of clay and topsoil.

(7) Niagara Falls, NY. Since 1976, a chemical waste management company has filled and capped three landfill cells in Niagara Falls, NY. The surface areas of the cells range from 2 to 5 acres. Records of leachate pumpage have been kept from 1983 and indicate annual withdrawals ranging from 1 to 11 inches. An evaluation of the performance of the facility during 1984 was reported to the USEPA Region II by Recra Research, Inc.

The data used in the simulations were obtained from a variety of sources. In most cases, daily rainfall and monthly temperature data were obtained from the nearest National Oceanic and Atmospheric Administration weather station. Solar radiation values stored in the HELP model were used for all simulations. Model input values for design data and soil and waste characteristics were determined from published reports describing the construction and operation of each landfill. In general, the information available on soil and waste characteristics, surface vegetation, runoff curve numbers, or evaporative depths was descriptive and sketchy, not quantitative; therefore, extensive use was made of default values stored in the HELP model.

The measured data used for comparison with the HELP model simulations were primarily lateral leachate drainage volumes. Measured runoff data was available from 11 landfill cells. Barrier soil percolation was measured at one landfill, although its suitability for model verification was limited. The measured data from very similar cells at the same landfill varied greatly from cell to cell. For four practically identical cells the range in total runoff was about 50 percent of the mean total runoff, and for lateral drainage the range was greater than 100 percent of the mean.

Runoff

Measured runoff data existed for eight cells at the University of Wisconsin and for three cells at Sonoma County, CA. Runoff was overpredicted for five cells by an average of 30 percent of the measured runoff, and underpredicted for six cells by an average of 20 percent of the measured runoff. Overall, runoff was overpredicted by 3 percent. Following these initial simulations, the curve numbers were varied to determine their effect on the overall model prediction of landfill performance. Five simulations were improved by a change in curve number--all had originally underpredicted runoff.

For the three cells at Sonoma County, it was obvious that the evapotranspiration and/or soil characteristics were controlling runoff volume and not the curve number. Because of this close interaction, it was difficult to assess the accuracy of the curve number method in the HELP model based on the field data in this report. However, the predicted runoff volumes appear overall to be in reasonable agreement with the measured results.

A comparison of measured and predicted runoff on a monthly basis for the University of Wisconsin cells indicated that the assumptions used in the HELP model for snowmelt runoff may not be appropriate. The model stores all precipitation on the surface when the mean daily temperature interpolated from the mean monthly temperature is below freezing. When this mean daily temperature rises above freezing, the precipitation is allowed to either run off or infiltrate. Since mean daily temperatures are computed in the HELP model based on mean monthly temperatures which are generally below freezing in Wisconsin for several consecutive months, no runoff was predicted by the HELP model during the winter. Instead, a large runoff volume was predicted during April of each year when temperatures warmed. This compared to measured results which showed significant runoff throughout the winter without an excessively large runoff in April. This discrepancy probably contributed to the overprediction of runoff for several cells.

Evapotranspiration

No suitable evapotranspiration field data from landfill sites was found for model testing. This was not unexpected due to the complexities involved in collecting this type of data. Yet, evapotranspiration is typically the single largest outflow component of the landfill system; therefore, small changes in evapotranspiration can have major impacts on volumes of lateral drainage and barrier soil percolation.

For those cells which had runoff data available, a surrogate variable for evapotranspiration was identified, and comparisons were made between measured and predicted results. The variable consisted of the sum of the water balance components which were not directly measured. In the case of the University of Wisconsin cells, the variable was the sum of evapotranspiration and change in moisture storage, ET+DS. For the Sonoma County cells, it was the sum of evapotranspiration, change in moisture storage, and percolation, ET+DS+PERC. The ET+DS variable was found to be underpredicted by an average of 4 percent of the measured values, whereas the ET+DS+PERC variable was underpredicted by an average of 25 percent. It is obviously rather complex to discern the meaning of these results since evapotranspiration, change in moisture storage, and percolation are all interrelated. The evidence suggests that values chosen for evaporative depths may have been too small.

Lateral Drainage and Percolation

Since measurements of barrier soil percolation volumes and leachate ponding depths were not available, the lateral drainage and barrier soil percolation submodel could only be evaluated using measured leachate collection data. One exception was the Boone County, KY cell where barrier soil percolation volumes were measured. However, the configuration of the clay liner and percolation collection pipe was such that vertical percolation did not actually occur; rather, the percolation flow paths were forced to converge radially toward the collection pipe. The attempt to simulate this percolation using the HELP model resulted in an overprediction of approximately 35 percent.

Lateral drainage was overpredicted by 10 percent of the measured drainage in two cells where very high leachate collection rates were observed. In three cells where very small quantities of leachate were collected, lateral drainage was underestimated by 97 percent of the measured drainage, although this difference only amounted to 1.4 inches per year. Of the remaining nine cells, lateral drainage was overpredicted by an average of 4 percent of the measured drainage in five covered cells and overpredicted by an average of 53 percent of the measured drainage in four permanently uncovered cells with a weathered waste surface that supported dense vegetation. Small errors in the hydraulic conductivities of the cover soils can cause large differences in the leachate production when the leachate production is small. Also the overpredictions may have been partially related to the manner in which the HELP model estimates unsaturated hydraulic conductivities. To linearly relate unsaturated hydraulic conductivity to moisture content between field capacity and saturation tends to overpredict unsaturated hydraulic conductivity. Thus, moisture is routed more quickly through the evaporative zone, contributing to larger leachate volumes and smaller evapotranspiration volumes.

The poor reproductions of lateral drainage for the uncovered cells at the University of Wisconsin and the three cells without subsurface liquid addition at Sonoma County were probably caused by poor estimates of the hydraulic conductivity of the surface layer. The field results could be reproduced by adjusting only the hydraulic conductivity of the surface layer by less than a factor of 10, within the range of its probable value. This result is understandable since cumulative lateral drainage is dependent on two main factors: the rate of infiltration into the lateral drainage layer and the rate of percolation through the liner beneath the drainage layer. The rate of percolation was very small in these cells; therefore, the rate of infiltration was the source of error.

Summary

The lack of adequate site description and measured water budget components affected the verification study in two ways. First, the lack of descriptive landfill information required the frequent use of default values in the HELP model which introduced additional uncertainty into the verification. Second, the lack of water balance outflow measurements limited the number of HELP outflow predictions that could be verified. These limitations restricted the ability of the study to isolate and test mathematical characterizations of specific physical processes, such as soil moisture storage and routing, evapotranspiration demand and its distribution through the soil profile, unsaturated vertical drainage, and details of the apportioning of leachate production between lateral drainage to collection systems and vertical percolation through the clay liner.

In addition, the variable degree of field measurement precision and reliability presented challenges in interpreting the data which did exist. None of the field data used in this report were collected specifically for verifying the HELP model; therefore, the field data were not always consistent with the needs of this study. For instance, the data available for the three largest landfills were collected while they were simultaneously undergoing expansion. In other cases, there was large variability in measured results between otherwise identical landfill cells. In general, the error in estimates of water budget components were much smaller than the variability in the field measurements for similar landfill cells. These results are very good in light of the fact that the precipitation data used in this study, which is known to be spatially highly variable, were not measured at most of the landfill sites. All of this required a significant amount of engineering judgment in interpreting the data for the HELP model comparisons.

Although a detailed verification of specific model components was not always possible, the data did confirm the model's overall utility in estimating a landfill water balance even without extensive knowledge of specific landfill characteristics. This was an important finding since the HELP model is typically used without a large amount of detailed landfill information.

The following conclusions are made. The field data verified the utility of the HELP model for estimating general landfill performance. However, not all model components were well tested due to the limited field data available. It is concluded that a laboratory and field monitoring program explicitly designed for HELP verification would be necessary for further refinement of specific model components. In addition, studies are needed to examine lateral drainage and percolation for small infiltration rates and flow through synthetic liners and in leakage detection or double liner systems.

The overall data base of long-term water budget measurements at landfills is poorly organized and too small to continually advance the state of the art in understanding landfill leachate generation and migration. More extensive monitoring activities are required to fill this gap.

Improvements to the HELP model are warranted in the areas of snowmelt, winter runoff, unsaturated hydraulic conductivities, and the selection of evaporative depths based on the results of this study.

SENSITIVITY ANALYSIS

A sensitivity analysis of the HELP model was performed to examine the effects of the major design parameters on components of the water budget for landfills. The analysis examined the effects of cover design, topsoil thickness, topsoil characteristics, vegetation, runoff curve number, evaporative depth, drainable porosity, plant available water capacity, hydraulic conductivity, drainage length, and liner slope on the water budget. Hydraulic conductivity values for the topsoil, lateral drainage layers and clay liners are the most important parameters in determining the water budget components. These parameters are particularly important in estimating the percolation through the landfill. Other design parameters tend to affect the apportionment between runoff, evapotranspiration and lateral drainage from the cover.

The interrelationship between parameters influencing the hydrologic performance of a landfill cover in the HELP model is complex. It is difficult to isolate one parameter and exactly predict its effect on the water balance without first placing restrictions on the values of the remaining parameters. With this qualification in mind, the following general summary statements are made.

The primary importance of the topsoil depth or thickness is in controlling the extent or existence of overlap between the evaporative depth and the head in the lateral drainage layer. Surface vegetation has a significant effect on evapotranspiration from soils with long flow-through travel times (low hydraulic conductivity) and large plant available water capacities; otherwise, the effect of vegetation on evapotranspiration is small. The general influence of surface vegetation on lateral drainage and barrier soil percolation is difficult to predict outside the context of an individual cover design. Clayey soils yield greater runoff and evapotranspiration, and less lateral drainage and barrier soil percolation. Simulations of landfills in colder climates and in areas of lower solar radiation are likely to show less evapotranspiration and greater lateral drainage and barrier soil percolation. An increase in the runoff curve number will increase runoff and decrease evapotranspiration, lateral drainage, and barrier soil percolation. As evaporative depth, drainable porosity or plant available water increase, evapotranspiration tends to increase while lateral drainage and barrier soil percolation tend to decrease; the effect on runoff is varied.

The sensitivity analysis shows that the ratio of lateral drainage to percolation is a positive function of the ratio of K_D/K_P and the average head above the liner. However, the average head is a function of Q_D/K_D and L/α. The quantity of lateral drainage, and therefore also the average head, is in turn a function of the infiltration. Therefore, the ratio of lateral drainage to percolation increases with increases in infiltration, and the ratio of K_D/K_P for a given drain and liner design. The ratio of lateral drainage to percolation for a given ratio of K_D/K_P increases with increases in infiltration and decreases in L/α. The percolation and average head above the liner are positive functions of the term L/α.

REVIEW OF TECHNICAL GUIDANCE

The information from the sensitivity analysis and the verification results were used to evaluate RCRA landfill design guidance and regulation. This evaluation showed that saturated hydraulic conductivity is the most important design parameter for minimizing percolation. Care should be taken to recommend the highest hydraulic conductivity that is commonly available for drainage media. Similarly, the lowest saturated hydraulic conductivity practically obtainable should be used as guidance for soil liners. Changes in other design parameters yield much smaller effects on percolation or leakage volumes if the values of these parameters are kept in a reasonable range.

SECTION 2

INTRODUCTION

BACKGROUND

Landfills have come to be a widely employed means for disposal of municipal, industrial and hazardous solid wastes. Storage of any waste material in a landfill poses several potential problems. Among these is the possible contamination of ground and surface waters by the migration of water or leachate from the landfill to adjacent areas. Given this potential problem, it is essential that the liquids management technology perform as expected during its development. It is also essential that the performance of the technology can be simulated or modeled with sufficient accuracy to design landfills to prevent migration of water from the facility. The modeling of the moisture movement through landfills is also important to review landfill designs and to determine the adequacy of the design and the limitations of the liquids management technology.

The Hydrologic Evaluation of Landfill Performance (HELP) model was developed to help hazardous waste landfill designers and evaluators estimate the magnitudes of components of the water budget and the height of water-saturated soil above barrier soil layers (liners). This quasi-two-dimensional, deterministic computer-based water budget model performs a sequential daily analysis to determine runoff, evapotranspiration, percolation, and lateral drainage for the landfill (cap, waste cell, leachate collection system, and liner) and obtain estimates of daily, monthly, and annual water budgets (1,2). The model does not account for lateral inflow or surface runon.

The determination of the magnitude of each component of the water budget is not a simple task. The interrelationships between climate, vegetation and soil characteristics and their effects on runoff, evapotranspiration and vertical drainage are very complex and not easily determined without a model. Therefore, a model can be very useful to verify that liquid management technology performs as anticipated, that regulations are practicable and achieve their goal, and that the technical guidance for design and evaluation is correct.

In the course of the development of any model, provisions should be taken to verify that the model accurately represents reality. Laboratory tests have been performed to verify the lateral drainage portion of the HELP model, but prior to this study the other portions of the model had only been calibrated and not verified. This report presents the results of efforts to verify the model using existing data collected at landfills, test cells and lysimeters.

SCOPE AND PURPOSE

This study consists of three parts. The main part is an attempt to verify the model using existing data. The purpose of this part of the study was to assess the adequacy of the model to simulate reality and to validate the use of the model to evaluate designs (generally with minimum information). Data sets were obtained at several landfill sites in different areas of the United States--California, Wisconsin, Kentucky and New York. The landfills varied in their designs, operating conditions and soil characteristics. In general, the landfill characteristics are loosely defined and permit a lot of latitude and uncertainty in the selection of values to describe the landfill. The water budget data from the different sites varied in the number of components measured--only leachate collection was measured at some while precipitation, runoff, percolation and leachate collection were measured at others. Consequently, the level of verification attempted varied from site to site, but efforts were made in all cases to isolate processes (evapotranspiration, runoff, percolation and lateral drainage) and to determine how accurately each is modeled.

The second part of this study is a sensitivity analysis of the principal parameters used in the HELP model. The purpose of this part of the study was to determine the parameters that need to be well defined and the likely effects of a change in the value of a parameter. This analysis also provided insight to interpret and explain the verification results. Several levels of detail and specificity were used in the sensitivity analysis. The lowest level of specificity examined the general effects of cover design, cover soil type, cover thickness and vegetation for three climates--cold and humid (Schenectady, NY), hot and humid (Shreveport, LA) and hot and semiarid (Santa Maria, CA). The next level of detail specifically examined the effects of runoff curve number, evaporative depth, drainable porosity and plant available water capacity for two cover designs and two climates using the same cover soil type, cover thickness and vegetation. The highest level of specificity examined only the proportioning of infiltrated water between the budget components of percolation and lateral drainage. This last analysis compared the effects of hydraulic conductivity of the barrier soil layer (liner), hydraulic conductivity of the lateral drainage layer, slope of the base of the lateral drainage layer and maximum lateral drainage length.

The third part of the study consists of an evaluation of the technical guidance developed to support the regulations regarding design and operation of a landfill. The purpose of this part of the study was to examine the technical guidance and regulations from the point of view of minimizing potential percolation or leakage through the liner at the base of the landfill in the best practicable manner. This evaluation examined the results of the laboratory and field verification studies and the sensitivity analysis to determine whether the technical guidance was practicable and achieved its objectives. The evaluation examined guidance on final covers, leachate detection, collection and removal systems and liners. Specifically, evaluation of the final cover guidance included effects of vegetation, vegetated cover soil thickness, drainage layer design and liner design. Evaluation of leachate detection, collection and removal systems includes examination of the hydraulic conductivity, slope and maximum drainage length of the drainage layer. Evaluation of liners included effects of liner thickness and hydraulic conductivity.

SECTION 3

MODEL DESCRIPTION

The HELP computer program models the effects of hydrologic processes on the water budget for landfills by performing daily, sequential analysis using a quasi-two-dimensional, deterministic approach. The dominant hydrologic considerations include precipitation in any form, surface storage, interception, surface evaporation, runoff, snowmelt, infiltration, vegetation, rooting depth, plant transpiration, soil evaporation, temperature, solar radiation, soil moisture storage, soil moisture potential, unsaturated flow, saturated flow, percolation and lateral drainage. The program handles each of these considerations, often in a simplified manner, in five main routines to estimate runoff, evapotranspiration, vertical drainage to liners, percolation through liners and lateral drainage from layers above liners. Several other routines interact with these routines, and these routines are involved with snowmelt, surface storage, synthetic flexible membrane liners and generation of daily temperature, solar radiation and leaf area index values. This section briefly describes the five major routines and the snowmelt and synthetic flexible membrane liner routines to provide a basis for understanding the approaches used in the sensitivity analysis and verification study, the results of the studies, and the conclusions. A more detailed description of the model is presented in the documentation report for the model (1).

The HELP model computes runoff by the Soil Conservation Service (SCS) runoff curve number method (3). Percolation is computed by Darcy's law, modified for unsaturated flow (1). Lateral flow is computed by a linearization of the Boussinesq equation, and evapotranspiration is determined by a method developed by Ritchie (4). The vertical percolation and evapotranspiration components of the HELP model originated with the CREAMS (5) program. The development presented here, however, reflects a significant advance beyond the CREAMS model in both of these areas. Each of these model components will be discussed in detail below.

RUNOFF AND INFILTRATION

The SCS curve number technique (3), as first implemented in the CREAMS model, was selected as a model to partition incoming rainfall or snowmelt between runoff and infiltration in the HELP model.

The SCS equation relates daily runoff, Q, to daily precipitation, P, and a watershed retention parameter, S, as follows:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \qquad (1)$$

where Q, P, and S are in inches.

The retention parameter, S, is a nonlinear function of soil moisture and vegetative cover density. This function is described by a series of empirical curves developed by SCS. An appropriate curve can be selected from the SCS manual (3) to match the desired surface cover for a landfill. The curve number, CN, is related to the retention parameter as follows:

$$S = \frac{1000}{CN} - 10 \qquad (2)$$

The actual value of S for any time during a simulation period is computed by the procedure described in CREAMS (5):

$$S = S_{max} \left[1 - \left(\frac{SM - WP}{UL - WP}\right)\right] \qquad (3)$$

where S_{max} = retention parameter value for a dry antecedent condition

SM = a depth-weighted estimate of soil moisture, vol/vol

WP = the lower limit of soil water storage or wilting point, vol/vol

UL = upper limit of soil water storage or total porosity of the soil, vol/vol.

To account for the nonuniform distribution of moisture in the soil profile, a weighting function which gives greater weight to moisture near the surface is used. The soil profile in the evaporative zone is divided into seven segments. These soil segments are used in the moisture routing scheme, and their soil moistures are averaged to compute the effective soil moisture.

Soil segments vary in thickness as follows: the uppermost segment has a thickness equal to 1/36 times the lesser of the depth from the surface to the barrier soil layer and the depth of the evaporative zone profile; the second layer has thickness equal to 5/36 of this profile, and the remaining five segments each have thicknesses equal to 1/6 of this profile. The depth-weighted retention parameter is computed as follows:

$$S = S_{max}\left[1 - \sum_{j=1}^{7} W_j \left(\frac{SM_j - WP_j}{UL_j - WP_j}\right)\right] \qquad (4)$$

where W_j = weighting factor for segment j

SM_j = soil moisture content of segment j

WP_j = wilting point of segment j

UL_j = upper limit of soil moisture content of segment j.

The weighting factors are identical to those used in CREAMS (5): for segments 1 through 7, these weighting factors are 0.111, 0.397, 0.254, 0.127, 0.063, 0.032, and 0.016, respectively.

Infiltration is computed as the difference between the daily precipitation and runoff computed by Equation 1, minus the daily surface evaporation. If the mean daily temperature is below 32°F, the precipitation is stored on the surface as snow and does not contribute to infiltration or runoff until the mean daily temperature rises above 32°F. The amount of melted snow is added to precipitation for use in Equation 1.

The amount of snowmelt on day i is computed as follows (3):

$$\begin{aligned} M_i &= 0 \text{ for } T_i \le 32°F \text{ or } SNO_{i-1} = 0 \\ M_i &= 0.06\,(T_i - 32) \text{ for } T_i > 32°F \\ &\quad \text{and } SNO_{i-1} \ge 0.06\,(T_i - 32) \\ M_i &= SNO_{i-1} \text{ for } T_i > 32°F \text{ and} \\ &\quad SNO_{i-1} < 0.06\,(T_i - 32), \end{aligned} \tag{5}$$

where M_i = amount of snow melted on day i, inches

T_i = mean temperature on day i, °F

SNO_{i-1} = amount of snow water on surface at the end of day i-1, inches.

EVAPOTRANSPIRATION

The evapotranspiration (ET) from a landfill cover is a function of the energy available, the vegetation, the soil transmissivity, and the soil moisture content. The potential ET is computed in the HELP model by a modified Penman method as described by Ritchie (4) and used in CREAMS (5):

$$E_o = \frac{1.28\ A\ H}{A + 0.68} \tag{6}$$

where E_o = potential ET, mm

A = slope of saturation vapor pressure curve

H = net solar radiation, langleys.

The daily potential ET is applied first to any free water available on the surface, thereby reducing the computed infiltration or the amount of snow on the surface. Any ET demand in excess of free surface water is exerted on the soil column for evaporation directly from the soil and for transpiration through the surface vegetation.

Soil evaporation proceeds in two stages: stage one, where evaporation is controlled by atmospheric demand, and stage two, where evaporation is limited by soil transmissivity. The potential evaporation from soil is computed as follows:

$$ES_o = E_o \exp(-0.4\ LAI) \tag{7}$$

where ES_o = potential evaporation from soil, mm

LAI = leaf area index (on scale of 0 to 3).

During the nongrowing season, LAI in Equation 7 is replaced by a winter cover factor that varies between 0 and 1.8 depending on the density of dead or dormant vegetation.

In stage one evaporation, soil water evaporation is equal to the potential soil water evaporation ES_o. An upper limit to the amount of stage one evaporation is computed as follows:

$$U = 9\ (a_s - 3)^{0.42} \tag{8}$$

where U = the upper limit for stage one evaporation, mm

a_s = soil transmissivity parameter for evaporation, $(\text{mm/day})^{1/2}$.

When the accumulated stage one evaporation less the infiltration exceeds the upper limit, U, any further soil water evaporation proceeds by the following equation:

$$ES_2 = a_s \left[t^{1/2} - (t - 1)^{1/2}\right] \tag{9}$$

where ES_2 = stage two evaporation from soil, mm

t = days since stage one ended.

Whenever the infiltration exceeds the cumulative evapotranspiration less the upper limit for stage one evaporation, evaporation reverts to the stage one process.

Potential plant transpiration is computed as

$$EP_o = \frac{E_o\ LAI}{3} \tag{10}$$

The potential ET may be satisfied entirely by evaporation from free water or from stage one or stage two evaporation from soil. If there is remaining atmospheric demand after these sources of ET have been exhausted, the demand will be satisfied by plant ET to a maximum of EP_o. The actual ET varies as a function of soil moisture and atmospheric demand as shown by Shanholtz and Lillard (6), Saxton et al. (7), and Sudar et al. (8). The following empirical relationship was developed from ET rate curves for no-till corn presented by Shanholtz and Lillard (6):

$$EP = EPD \left(1.20 - \frac{EPD}{6.35} + \frac{SM - WP}{FC - WP} \right) \qquad (11)$$

where EP = actual plant ET, mm

EPD = actual plant ET demand, mm

$= E_o - ES - ESS$ if $EP_o > E_o - ES - ESS$

$= EP_o$ if $EP_o \leq E_o - ES - ESS$

ES = actual soil water evaporation, mm

ESS = that portion of the total evapotranspiration met from precipitation or snow, mm

SM = soil moisture content, vol/vol

WP = wilting point moisture content of the soil, vol/vol

FC = field capacity of the soil, vol/vol.

The soil moisture, wilting point, and field capacity values used in Equation 11 are depth-weighted using the same weighting coefficients used for computation of the retention factor used in Equation 1.

VERTICAL MOISTURE FLOW

The vertical flow submodel is depicted in Figure 1 as it may be implemented for simulation of moisture movement in a landfill cover. When applied to an open landfill or to a landfill with multiple barrier soil layers, soil or waste layers below the top barrier soil layer are represented by fewer segments.

The input to the vertical flow model is the infiltration estimate. Output from the model is divided between lateral flow and vertical percolation through the barrier soil layer. Drainable moisture, that in excess of field capacity, is transferred through the profile by storage routing procedures.

Storage routing through segments of the model consists of simultaneous solution of Darcy's law and an equation of continuity. The model does not account for water movement by capillary action. Darcy's law is represented as

$$Q = K \frac{dh}{dl} \qquad (12)$$

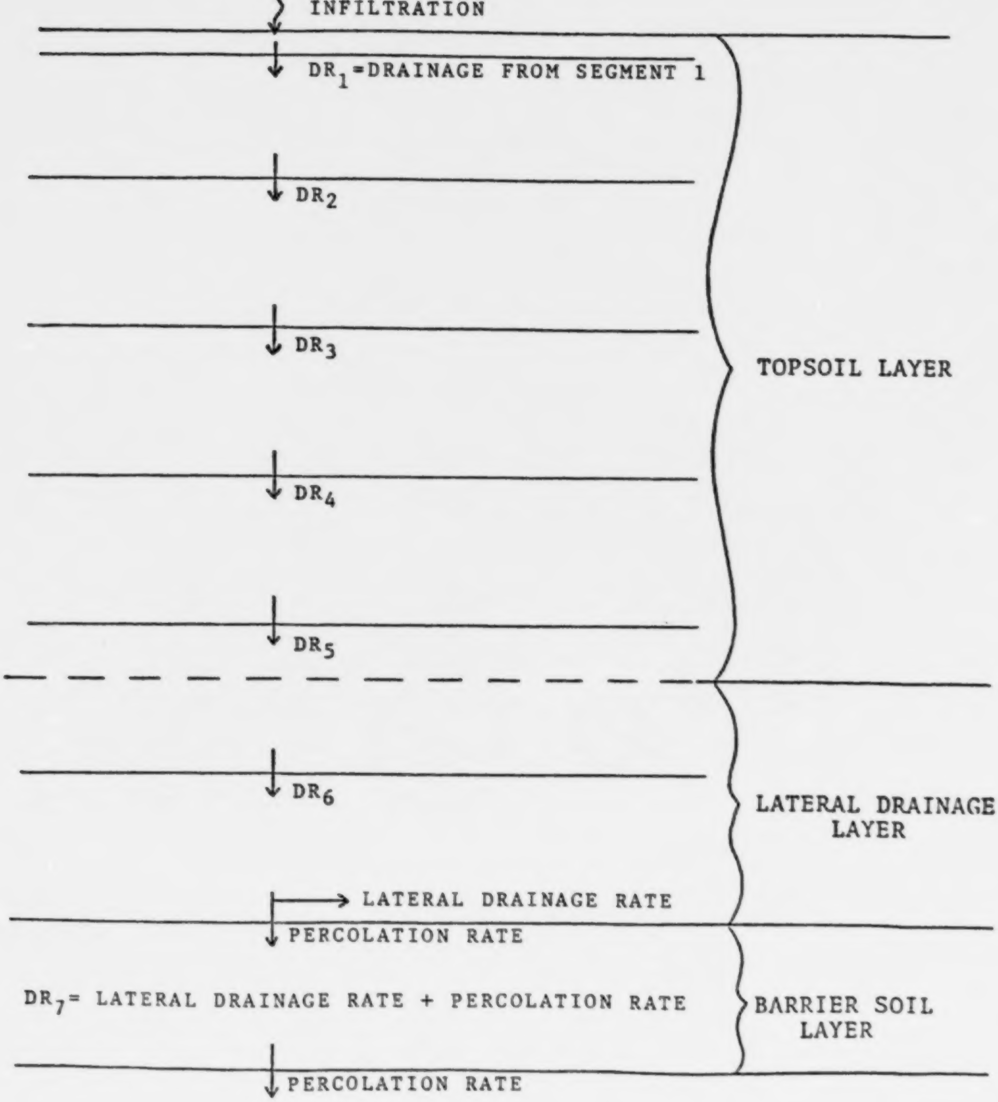

INFILTRATION
DR1=DRAINAGE FROM SEGMENT 1
DR2
DR3
DR4
DR5
DR6
TOPSOIL LAYER
LATERAL DRAINAGE LAYER
LATERAL DRAINAGE RATE
PERCOLATION RATE
DR7= LATERAL DRAINAGE RATE + PERCOLATION RATE
BARRIER SOIL LAYER
PERCOLATION RATE

Figure 1. Vertical flow submodel for landfill cover.

where Q = rate of vertical flow, inches/day

K = hydraulic conductivity, inches/day

h = gravitational head, inches

l = length in the direction of flow, inches.

Free outfall is assumed from each segment such that dh/dl may be set equal to unity, and Q is equal to the hydraulic conductivity. This assumption is acceptable only if the conductivity of the profile is constant or increases with depth. Because this assumption is not met at the interface between the seventh segment and the barrier layer in Figure 1, a different procedure is employed at the top interface of a barrier layer.

The rate of vertical moisture flow in soil varies with soil moisture content. When the soil is fully saturated, the flow rate is equal to the saturated hydraulic conductivity, and when the moisture content is reduced to field capacity, the flow rate is zero. In the HELP model the hydraulic conductivity is taken to be a linear function of soil moisture:

$$K_u = K_s \frac{SM - FC}{UL - FC} \qquad (13)$$

where K_u = unsaturated hydraulic conductivity, inches/day

K_s = saturated hydraulic conductivity, inches/day

SM = soil moisture content, vol/vol

FC = soil moisture content at field capacity, vol/vol

UL = total porosity or the soil moisture content at saturation, vol/vol.

The change in storage in a segment from mid time period i-1 to mid time period i may be written as the sum of one-half of the net drainage from the previous time period and one-half of the net drainage at the end of the current time period. Therefore,

$$SM_i = SM_{i-1} + 1/2\ NDR_i + 1/2\ NDR_{i-1} \qquad (14)$$

where SM_i = soil moisture at the end of the current time interval (mid-time period)

SM_{i-1} = soil moisture at the end of the previous time interval (mid-time period)

NDR = net drainage

and

$$NDR_i(j) = \Big[DR_i(j-1) - DR_i(j) - ET_i(j)\Big]\,\Delta t \qquad (15)$$

where j = segment number

i = time period

DR = drainage rate

Δt = the time interval.

The drainage rate from a segment is written as

$$DR_i = K_s \left[\frac{\left(\dfrac{SM_i + SM_{i-1}}{2}\right) - FC}{UL - FC}\right] \qquad (16)$$

Equations 14, 15 and 16 may be solved simultaneously for $DR_i(j)$, knowing SM_{i-1} from the previous time interval. The resulting drainage from segment j is as follows:

$$\begin{aligned} DR_i(j) = 2\,K_s(j)\, & \Big\{SM_{i-1}(j-1) + 1/2\; NDR_{i-1}(j) \\ & + \Big[1/2\; DR_i(j-1)\;\Delta t\Big] - \Big[1/2\; ET_i(j)\;\Delta t\Big] - FC(j)\Big\} \\ & / \;\Big\{2\Big[UL(j) - FC(j)\Big] + \Big[K_s(j)\;\Delta t\Big]\Big\} \end{aligned} \qquad (17)$$

The routing proceeds from the top segment, where incoming drainage is infiltration (rainfall less surface evaporation), to the seventh segment in Figure 1 where the drainage out is divided between percolation through the barrier soil layer and lateral drainage above the barrier soil layer.

PERCOLATION

An accurate estimate of percolation rate through a barrier soil layer cannot be obtained using the routing procedure described in the vertical flow submodel because of the discontinuity at the interface with the barrier soil layer. Percolation is modeled as Darcian flow where the percolation rate is computed as:

$$Q_p = K_p \frac{TH + T_c}{T_c} \qquad (18)$$

where Q_p = the rate of percolation through the barrier soil layer

K_p = the saturated hydraulic conductivity of the barrier soil layer

TH = the total head in the profile above the barrier soil layer

T_c = the thickness of the barrier soil layer.

To reduce the complexity of the percolation model, the drainable porosity of the barrier soil layer is considered negligible; that is, the barrier soil layer is assumed to be saturated at all times. This assumption has the effect that percolation stops as soon as there is no head above the barrier soil layer. In fact, if the barrier soil is a typical clay, it would continue to drain at a very low rate until the drainable water is depleted. If the drainable porosity of the clay were 1 percent and the thickness of the barrier soil layer were 60 cm, 0.6 cm of water could drain from the layer after all drainable water was removed from the profile above the barrier soil layer. Because the hydraulic conductivity of clay is very low (on the order of 10^{-7} cm/sec), it would require several months to deplete the drainable water from the clay. Further, it must be considered that the percolation of water from the soil profile into the drainable volume of the clay will also proceed at a slow rate due to the low hydraulic conductivity of the clay. Therefore, under humid conditions, the drainable porosity of the barrier soil layer assumption will have a negligible effect; under arid conditions with occasional wetting, the amount of percolation may be underpredicted. The underprediction, however, would be largely compensated over extended simulation periods.

Percolation through barrier soil layers having a synthetic membrane liner is also modeled by Darcy's law. The model uses the same equation (Equation 18) and routine to compute the quantity of percolation as in the absence of a synthetic membrane but uses a different hydraulic conductivity for the barrier soil. The model computes a resultant hydraulic conductivity of the layer and synthetic liner by multiplying the hydraulic conductivity of the soil by the leakage fraction of the synthetic liner. This resultant hydraulic conductivity is used in Equation 18 to compute percolation through soil liners with synthetic membranes.

LATERAL FLOW SUBMODEL

The lateral flow submodel of the HELP program is based on a linearization of the steady-state Boussinesq equation performed by Skaggs (9) which yielded the following equation:

$$Q_D = \frac{2\, K_D\, \bar{y}\, h_o}{L^2} \tag{19}$$

where Q_D = lateral drainage rate

K_D = hydraulic conductivity for lateral flow

$\bar{y}$ = average thickness of flow

h_o = elevation of water surface at $x = L$

x = lateral distance measured from drain

L = maximum length to drain.

The model configuration is shown in Figure 2 for a landfill having a drainage length of L and a drainage slope of α.

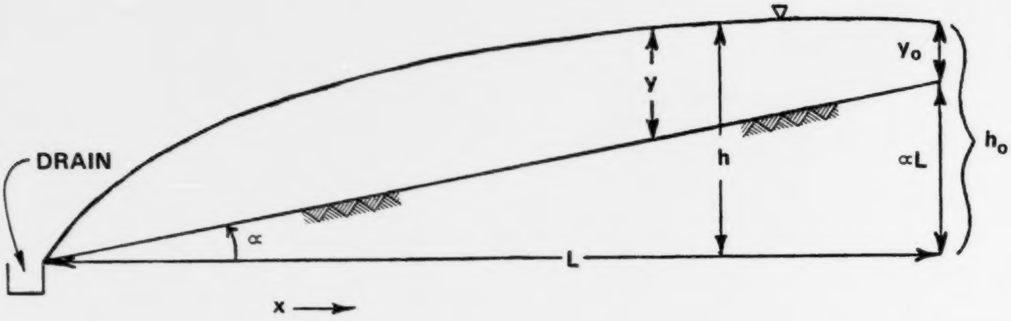


Figure 2. Configuration of lateral drainage model.

The vertical flow submodel simulates vertical flow for the entire cross section shown in Figure 2. Therefore, the thickness of the saturated zone computed in the vertical flow submodel corresponds to $\bar{y}$. Using a finite difference model, developed by Skaggs (9) to solve the Boussinesq equation, lateral drainage rates and water profiles were generated for nine combinations of α and L with $\bar{y}$ ranging from 0.2 to 1.0 m to obtain correction factors for the linearized Boussinesq equation.

Equation 19 may be rewritten with the correction factor as follows:

$$Q_D = \frac{2\, C_1\, K_D\, \bar{y}\, h_o}{L^2} \qquad (20)$$

where

$$h_o = y_o + \alpha\, L \qquad (21)$$

and y_o = depth of saturation at x = L

α = fractional slope at surface of liner

C_1 = correction factor

$$= 0.510 + 0.00205\, \alpha\, L \qquad (22)$$

The variables, y_o and h_o, are unknown during the simulation; therefore, a relationship between $\bar{y}$ and y_o was developed of the following form:

$$y_o = C_2 \bar{y} \qquad (23)$$

where

$$C_2 = \left(\frac{\bar{y}}{\alpha L}\right)^{0.16} \qquad (24)$$

Therefore, the final form of Equation 19 is:

$$Q_D = \frac{2 K_D \bar{y} (0.510 + 0.00205 \alpha L) \left[\bar{y} \left(\frac{\bar{y}}{\alpha L}\right)^{0.16} + \alpha L\right]}{L^2} \qquad (25)$$

where the units of $\bar{y}$ and L are in inches and α is dimensionless.

SECTION 4

SENSITIVITY ANALYSIS

This chapter examines the sensitivity of the HELP model to variations in values of selected input parameters. This information is useful in a variety of ways. It can aid the design engineer in selecting preliminary design alternatives for specific soil characteristics, geographical regions, surface vegetation, and layer thicknesses. It can serve as a basis for evaluating and establishing technical guidelines for regulatory agencies. It can also provide additional insight to the HELP model user in understanding the importance and interaction of specific variables in controlling the water balance within a landfill. Finally, it can assist in evaluating the suitability of methodologies used in the HELP model.

The parameters included in this analysis are listed in Table 1. They are grouped according to their role in either cover design or drainage and percolation design. Each group will be examined separately.

TABLE 1. PARAMETERS SELECTED FOR SENSITIVITY ANALYSIS

Analysis of Cover Design

- Topsoil type
- Cover soil thickness
- Surface vegetation
- Runoff curve number
- Evaporative depth
- Drainable porosity
- Plant available water
- Geographical location
- Municipal vs. hazardous waste cover design

Analysis of Percolation and Drainage Design

- Hydraulic conductivity of barrier soil layer
- Hydraulic conductivity of lateral drainage layer
- Slope of lateral drainage layer
- Drainage length

LANDFILL COVER

This analysis for landfill covers is divided into two parts. Both parts examine the effect of geographical location, municipal versus hazardous waste cover design, and topsoil characteristics. In addition, Part 1 considers topsoil thickness and surface vegetation, whereas Part 2 considers runoff curve number, evaporative depth, drainable porosity, and plant available water. The following discussion applies to Parts 1 and 2.

To determine the effect of various climatological regimes on cover performance, three locations were studied--Santa Maria, CA; Schenectady, NY; and Shreveport, LA. These locations represent a wide range in levels of precipitation, temperature, and solar radiation as summarized in Table 2. Default values for precipitation, temperature, solar radiation, and leaf area index are stored in the HELP model for each site and were used for the sensitivity analysis simulations. The period of record for the daily precipitation values stored in the HELP model is 1974 through 1978.

In addition, two cover designs were examined as shown in Figure 3. One was typical of hazardous waste landfills where topsoil overlies a 1-foot-thick lateral drainage layer (hydraulic conductivity = 3×10^{-2} cm/sec, slope = 0.03, drainage length = 200 feet) which further overlies a 2-foot-thick clay liner or barrier soil layer (hydraulic conductivity = 1×10^{-7} cm/ sec). The second was typical of municipal sanitary landfills where topsoil overlies a two-foot-thick barrier soil layer (hydraulic conductivity = 1×10^{-6} cm/sec).

Two types of topsoil were considered in the cover designs: sandy loam and silty clayey loam. The sandy loam characteristics were those of the HELP model default soil texture 8, which represents Unified Soil Classification System (USCS) soil class SM and U.S. Department of Agriculture (USDA) soil class SL. The silty clayey loam characteristics were those of the HELP model default soil texture 15, which represents USCS soil class CL and USDA soil class SICL.

Part 1

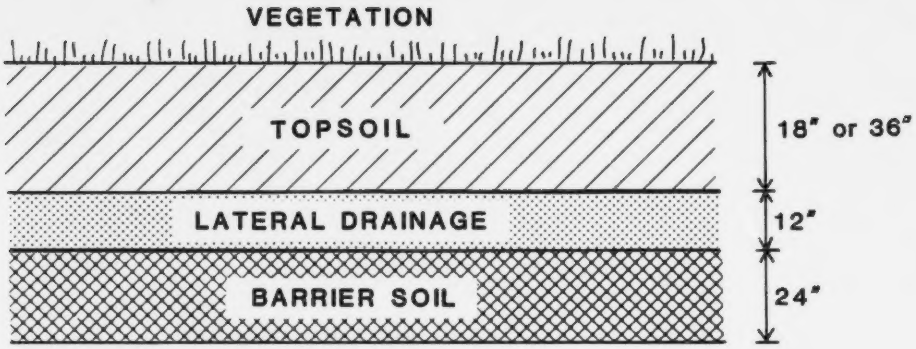
In Part 1, the vegetative cover was designated as either good grass or poor grass. This selection dictated the values for runoff curve number and evaporative depth, and influenced the value of the hydraulic conductivity of the topsoil. For a given vegetative cover, the runoff curve number was obtained from Figure 4 of the HELP Model User's Guide (2) using the minimum infiltration rate given in Table 10 of the same reference for sandy loam or silty clayey loam. The depth of the evaporative zone was chosen as 7 inches for poor grass and 14 inches for good grass, based on recommendations contained in the HELP model.

Table 3 summarizes the parameter combinations examined under Part 1 and presents the results of the HELP model simulations as percentage of precipitation. Simulations for the hazardous waste cover design were performed for both soil types, whereas simulations for the municipal design were performed only for sandy loam. The same results are presented in the form of bar graphs

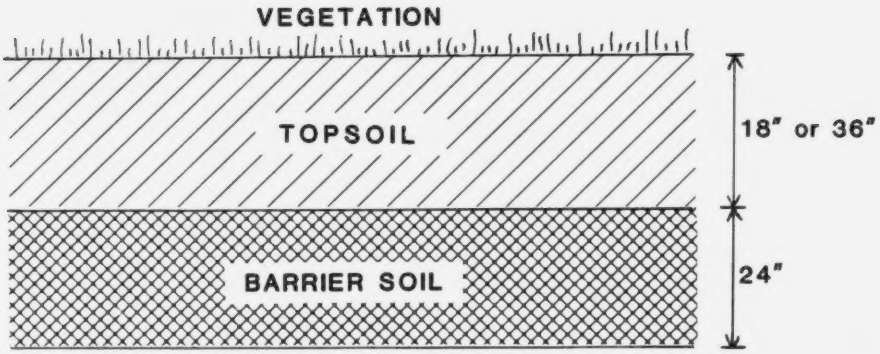
TABLE 2. CLIMATOLOGICAL REGIMES

Climatological Variable	Location		
	Santa Maria, CA	Schenectady, NY	Shreveport, LA
Precipitation*			
Mean Annual (in.)	14	48	44
Mean Winter (Nov-Apr) (in.)	12	19	22
Mean Summer (May-Oct) (in.)	2	29	22
Temperature			
Mean Annual (°F)	57	49	66
Mean Jan. (°F)	51	23	47
Mean July (°F)	62	73	83
Days with Minimum Below 32°F	24	129	37
Solar Radiation			
Mean Daily (langleys)	450	290	410

* These mean values are for the period simulated by the HELP model in this section, 1974-1978.


VEGETATION
TOPSOIL
LATERAL DRAINAGE
BARRIER SOIL
18" or 36"
12"
24"

a) Hazardous Waste Landfill Cover Design


VEGETATION
TOPSOIL
BARRIER SOIL
18" or 36"
24"

b) Municipal Landfill Cover Design

Figure 3. Cover designs for sensitivity analysis.

TABLE 3. SENSITIVITY OF WATER BUDGET COMPONENTS TO LOCATION, VEGETATION, AND TOPSOIL TYPE AND DEPTH

Description*				Average Annual Volume (Percent Precipitation)**						
				Hazardous Waste Design				Municipal Design		
Site	Soil Type	Veg.	Soil Depth (in.)	Runoff	ET	Lat.† Drng.	Barrier†† Perc.	Runoff	ET	Barrier‡ Perc.
CA	SL	GG	18	0.0	53.4	43.4	4.2	8.8	58.1	34.2
CA	SL	GG	36	0.0	53.6	43.2	4.2	3.1	55.1	42.9
CA	SL	PG	18	3.0	52.0	41.4	4.2	11.2	52.4	36.9
CA	SL	PG	36	3.0	52.2	41.2	4.2	5.6	52.5	42.6
CA	SICL	GG	18	7.4	73.1	18.1	2.0			
CA	SICL	GG	36	7.4	73.1	18.1	2.0			
CA	SICL	PG	18	21.6	61.4	15.0	2.2			
CA	SICL	PG	36	21.6	61.4	15.0	2.2			
LA	SL	GG	18	0.2	52.9	43.8	3.1	2.2	66.3	31.6
LA	SL	GG	36	0.2	53.0	43.7	3.1	0.2	56.6	42.6
LA	SL	PG	18	4.4	51.6	40.6	3.1	7.5	56.2	35.6
LA	SL	PG	36	4.4	51.8	40.5	3.1	4.6	52.3	42.4
LA	SICL	GG	18	8.5	73.9	15.0	2.1			
LA	SICL	GG	36	8.6	74.1	14.7	2.1			
LA	SICL	PG	18	22.3	64.2	11.3	2.0			
LA	SICL	PG	36	22.3	64.2	11.3	2.0			
NY	SL	GG	18	0.04	50.9	45.6	2.5	9.5	60.6	28.9
NY	SL	GG	36	0.04	51.0	45.5	2.5	3.5	54.3	41.2
NY	SL	PG	18	2.2	50.1	44.0	2.5	13.4	53.3	32.1
NY	SL	PG	36	2.2	50.2	43.9	2.5	5.5	50.9	42.4
NY	SICL	GG	18	7.4	63.8	25.2	2.0			
NY	SICL	GG	36	6.7	63.9	25.7	2.0			
NY	SICL	PG	18	19.2	57.3	20.3	1.9			
NY	SICL	PG	36	19.2	57.2	20.3	1.9			

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* CA = Santa Maria, CA; LA = Shreveport, LA; NY = Schenectady, NY; SL = sandy loam (HELP default texture 8); SICL = silty clayey loam (HELP default texture 15); GG = good grass; PG = poor grass. Curve numbers were selected from Table 10 and Fig. 4 in Ref. 2. Evaporative depths were 14 inches for GG and 7 inches for PG.

** Change in storage is not included in this table; therefore, the water balance components shown do not always sum to 100.0%.

† Slope = 3%; drainage length = 200 ft; hydraulic conductivity = 3 x 10^{-2} cm/sec.

†† Hydraulic conductivity = 10^{-7} cm/sec.

‡ Hydraulic conductivity = 10^{-6} cm/sec.

in Figures 4 and 5. Here, the height of each bar segment represents the corresponding water balance component in mean annual inches.

Topsoil Depth--

As seen in Table 3, negligible differences existed between the 18- and 36-inch soil depth simulations for the hazardous waste design. For this reason only the results for 18-inch depth are included in Figure 4. These small differences are not surprising considering that both soil depths were sufficiently great so that no overlap existed between the evaporative zone and the head in the lateral drainage layer. This case is contrasted with the municipal design where larger heads (due to the lack of lateral drainage) interacted with the evaporative zone and increased evapotranspiration and runoff. At the same time, the larger heads increased percolation through the barrier soil. These increases in percolation over the hazardous waste design ranged from 800 to 1700 percent. The permeability of the barrier soil for the municipal design was 10 times as large as that for the hazardous waste design, which could account for a maximum of a 1000-percent increase in percolation.

For the municipal design, significant differences existed between the 18- and 36-inch soil depth simulations. Runoff and evapotranspiration were greater for the 18-inch depth, indicating that the head above the barrier soil layer maintained higher moisture contents in the evaporative zone. However, percolation was greater from the 36-inch depth due to its ability to accommodate higher heads and longer sustaining heads since evapotranspiration was limited to the top 7 to 14 inches of the cover.

Surface Vegetation--

In comparing the effect of good and poor grass, one would expect good grass to increase evapotranspiration and decrease runoff. Evapotranspiration would be increased due to an increased plant demand for moisture. Runoff would be decreased due to a reduced runoff curve number, a drier topsoil due to the greater evapotranspiration, and an increased hydraulic conductivity of the evaporative zone corresponding to an increased root density. The results of the HELP model simulations in Table 3 and Figures 4 and 5 confirm these effects. However, the influence of surface vegetation on the volume of lateral drainage and barrier soil percolation is varied. For the hazardous waste design, the increase in infiltration with good grass was greater than the increase in evapotranspiration, resulting in a larger volume of lateral drainage and a negligible change in barrier soil percolation. For the municipal design, the high heads above the barrier soil assisted evapotranspiration by maintaining higher moisture levels for plant uptake and hindered infiltration by maintaining higher antecedent moisture conditions; therefore, the increase in evapotranspiration was greater than the increase in infiltration. This resulted in a trend toward decreased barrier soil percolation for good grass.

It should be recognized that good grass could not be maintained in the climate of Santa Maria, CA, by rainfall alone, as assumed in this analysis. An additional sprinkler system water inflow component would be required to make the conditions realistic. However, the careful regulation of this surface-applied water would not change the results regarding lateral drainage or barrier soil percolation.

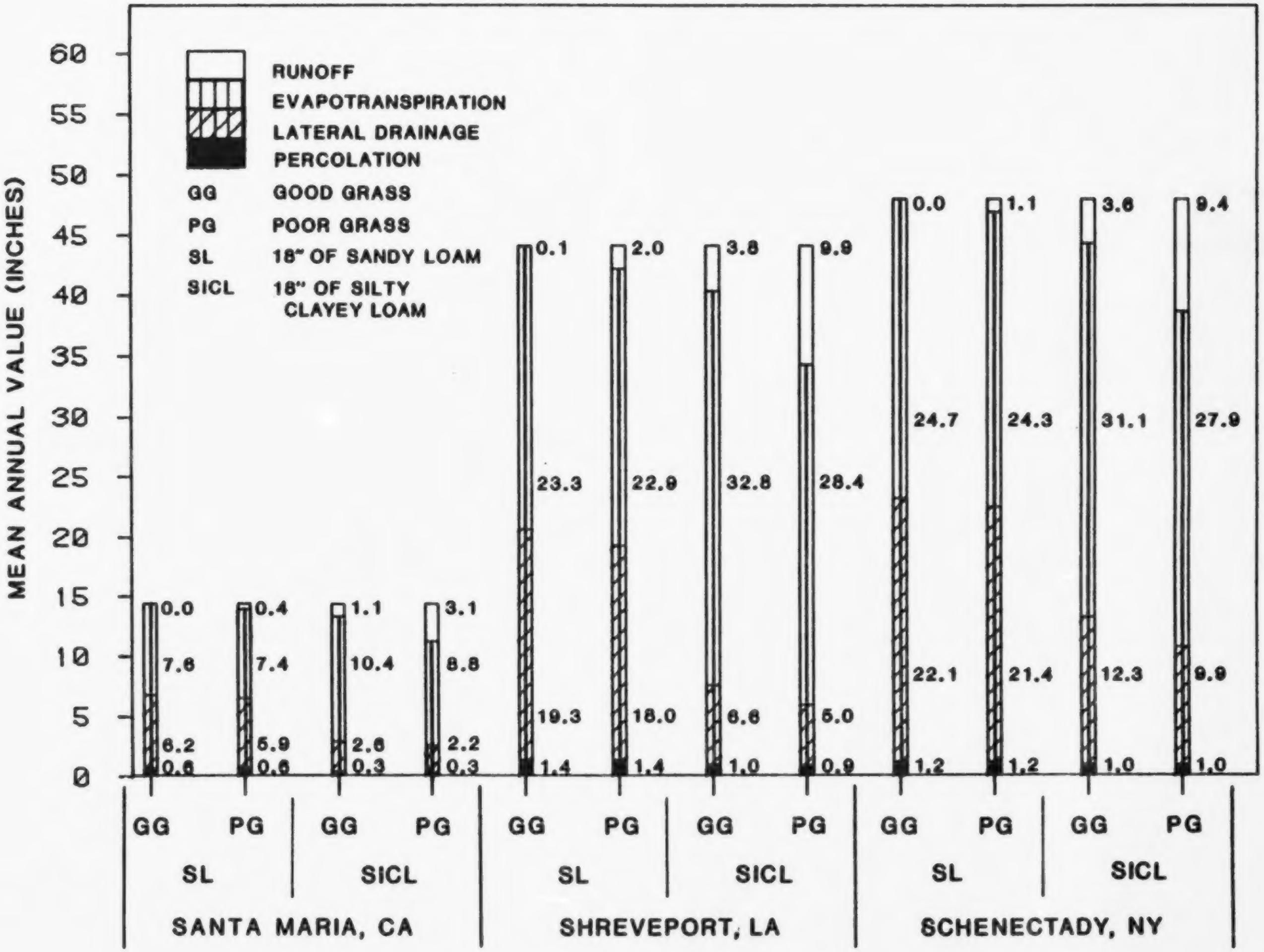

Figure 4. Bar graph for hazardous waste cover design showing effect of surface vegetation, topsoil type, and location.

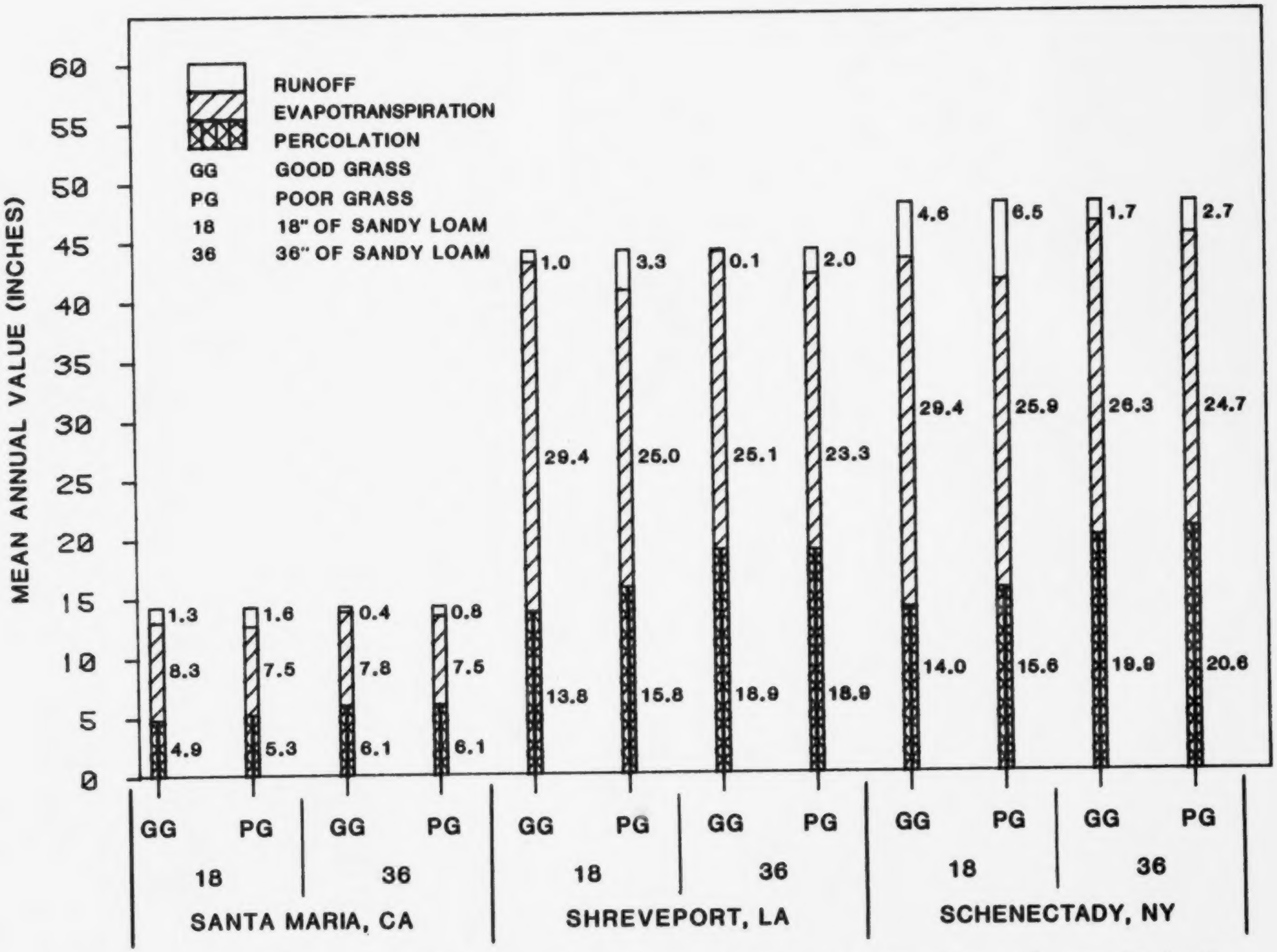

Figure 5. Bar graph for municipal cover design showing effect of topsoil depth, surface vegetation, and location.

Topsoil Type--

The results show that the clayey topsoil increased both runoff and evapotranspiration, which in turn decreased lateral drainage and barrier soil percolation. The increase in runoff was due primarily to the larger runoff curve number selected by the HELP model for clayey soils using the minimum infiltration rate method (2). The increase in evapotranspiration was due to: (a) the lower hydraulic conductivity of the clayey soil which slowed the drainage rate and maintained moisture levels above field capacity for longer periods of time, thus allowing evapotranspiration to deplete larger volumes of moisture, and, more importantly, (b) the larger plant available water capacity (field capacity minus wilting point) which left a larger moisture reservoir available for evapotranspiration losses after drainage ended.

Geographical Location--

Daily potential evapotranspiration as computed in the HELP model is a function of daily temperature and daily solar radiation. Of the three locations considered in this analysis, Schenectady, NY, experiences the lowest temperature and the lowest mean solar radiation. Consequently, for the hazardous waste design, the HELP model simulations show the least evapotranspiration (as percent precipitation) for Schenectady. However, the simulations show a slightly greater evapotranspiration percentage at Shreveport for clay soils even though Santa Maria experiences higher temperatures and greater solar radiation. The long travel time through clay soils combined with the higher average soil moisture levels at Shreveport (due to greater rainfall) probably contributes to this increased evapotranspiration percentage. Rainfall is more uniformly distributed throughout the year in Shreveport, while precipitation in Santa Maria occurs primarily during the winter months.

For the municipal designs, simulated evapotranspiration percentages for Santa Maria were among the lowest. This was probably related to the greater rainfall amounts at the other locations combined with the hydraulically restrictive barrier soil layer which created higher heads in the evaporative zone; thus, more water was subjected to potential evapotranspiration for a longer period of time. Consequently, the evapotranspiration percentages tended to be larger for Shreveport and Schenectady. In actuality, the depth of root penetration would probably vary between the sites for the same degree of vegetation due to effects of climate. If this were considered, evaporative depths and therefore evapotranspiration would likely be somewhat greater than indicated herein for the drier climate of Santa Maria.

Part 2

The effects of runoff curve number, evaporative depth, drainable porosity, and plant available water are discussed below. For this analysis, the vegetation was assumed to be fair grass. Tables 4 and 5 summarize the parameter combinations examined under Part 2 and present the results of the HELP simulations as percentage of precipitation. Figures 6 through 13 illustrate the same results, with values in mean annual inches.

Runoff Curve Number--

The runoff curve number was varied from 65 to 90 for the sandy loam and from 75 to 95 for the silty clayey loam. The depth of the evaporative zone

TABLE 4. SENSITIVITY OF WATER BUDGET COMPONENTS TO EVAPORATIVE DEPTH AND CURVE NUMBER

Description*				Average Annual Volume (Percent Precipitation)**						
				Hazardous Waste Design				Municipal Design		
Site	Soil Type	Evap Depth (in.)	Curve Number	Runoff	ET	Lat.† Drng.	Barrier†† Perc.	Runoff	ET	Barrier‡ Perc.
CA	SL	10	65	0.1	52.7	43.6	4.2	7.1	53.8	39.9
CA	SL	10	80	2.6	51.9	41.9	4.2	8.7	53.0	39.1
CA	SL	10	90	11.3	49.5	35.9	4.1	14.4	50.4	36.0
CA	SICL	10	75	5.5	70.8	22.1	2.2			
CA	SICL	10	85	12.7	67.6	18.0	2.2			
CA	SICL	10	95	34.4	57.3	6.4	1.6			
CA	SL	4	75	1.1	41.3	53.3	4.5	8.9	42.9	48.5
CA	SL	10	75	1.1	52.4	42.9	4.2	7.8	53.4	39.6
CA	SL	18	75	1.3	61.9	34.1	3.9	6.9	63.8	30.6
CA	SICL	4	85	12.6	53.3	30.5	3.7			
CA	SICL	10	85	12.7	67.6	18.0	2.2			
CA	SICL	18	85	12.0	77.0	11.2	1.2			
LA	SL	10	65	0.5	52.1	44.1	3.1	2.0	57.9	39.4
LA	SL	10	80	4.2	50.9	41.6	3.1	5.1	55.9	38.3
LA	SL	10	90	15.3	47.1	34.5	3.0	15.6	49.1	34.8
LA	SICL	10	75	5.8	71.2	20.3	2.3			
LA	SICL	10	85	13.5	69.6	14.5	2.2			
LA	SICL	10	95	36.5	59.0	3.0	1.4			
LA	SL	4	75	2.0	38.8	55.7	3.2	8.2	45.1	45.2
LA	SL	10	75	2.1	51.6	43.0	3.1	3.3	57.0	39.0
LA	SL	18	75	2.3	62.4	32.0	3.0	3.0	66.5	30.2
LA	SICL	4	85	12.4	55.6	28.8	2.9			
LA	SICL	10	85	13.5	68.1	14.4	2.1			
LA	SICL	18	85	14.3	75.8	8.1	1.2			

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* CA = Santa Maria, CA; LA = Shreveport, LA; SL = sandy loam (HELP model default texture 8); SICL = silty clayey loam (HELP model default texture 15). Fair grass was used for all cases.

** Change in storage is not included in this table; therefore, the water balance components shown do not always sum to 100.0%.

† Slope = 3%; drainage length = 200 ft; hydraulic conductivity = 3 x 10^{-2} cm/sec.

†† Hydraulic conductivity = 10^{-7} cm/sec.

‡ Hydraulic conductivity = 10^{-6} cm/sec.

TABLE 5. SENSITIVITY OF WATER BUDGET COMPONENTS TO DRAINABLE POROSITY AND PLANT AVAILABLE WATER

Description*			Average Annual Volume (Percent Precipitation)**						
			Hazardous Waste Design				Municipal Design		
Site	DP	PAW	Runoff	ET	Lat.† Drng.	Barrier†† Perc.	Runoff	ET	Barrier‡ Perc.
CA	0.18	0.07	1.07	48.51	46.45	4.31	8.57	49.78	42.16
CA	0.18	0.13	1.14	52.54	42.83	4.22	7.87	53.55	39.41
CA	0.18	0.20	1.30	56.43	39.43	4.12	7.06	57.18	37.02
CA	0.10	0.13	1.17	48.87	47.38	4.33	10.48	50.40	40.02
CA	0.18	0.13	1.14	52.53	42.81	4.22	7.87	53.55	39.41
CA	0.27	0.13	1.1	55.8	39.6	4.1	5.22	57.34	38.20
LA	0.18	0.07	2.08	47.38	47.12	3.12	4.36	54.57	40.08
LA	0.18	0.13	2.15	51.74	42.86	3.08	3.45	57.05	38.84
LA	0.18	0.20	2.26	55.68	38.92	3.04	2.98	59.99	36.69
LA	0.10	0.13	2.10	46.93	47.66	3.12	6.63	55.24	37.65
LA	0.18	0.13	2.15	51.74	42.86	3.08	3.45	57.05	38.84
LA	0.27	0.13	2.2	55.7	38.8	3.0	2.32	59.60	37.49

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* CA = Santa Maria, CA; LA = Shreveport, LA; DP = drainable porosity (vol/vol); PAW = plant available water (vol/vol). All cases are for sandy loam top soil (HELP model default texture 8); fair grass; evaporative depth = 10 in.; and curve number = 75.

** Change in storage is not included in this table; therefore, the water balance components shown here do not always sum to 100.0%.

† Slope = 3%; drainage length = 200 ft; hydraulic conductivity = 3×10^{-2} cm/sec.

†† Hydraulic conductivity = 10^{-7} cm/sec.

‡ Hydraulic conductivity = 10^{-6} cm/sec.

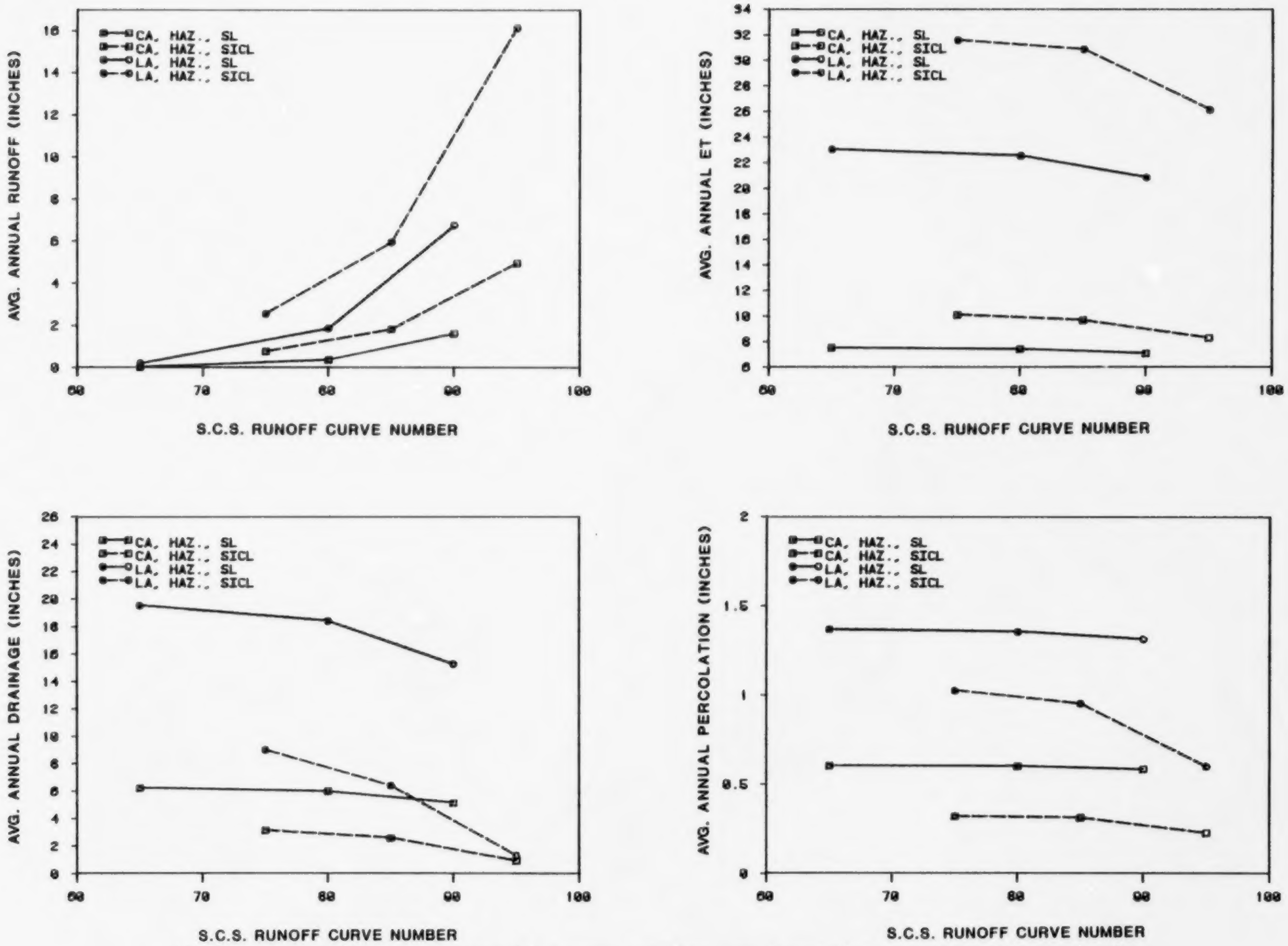


Figure 6. Effect of runoff curve number on hazardous waste cover design.
(CA = Santa Maria, California; LA = Shreveport, Louisiana;
HAZ = hazardous waste design; SL = sandy loam topsoil;
SICL = silty clayey loam topsoil)

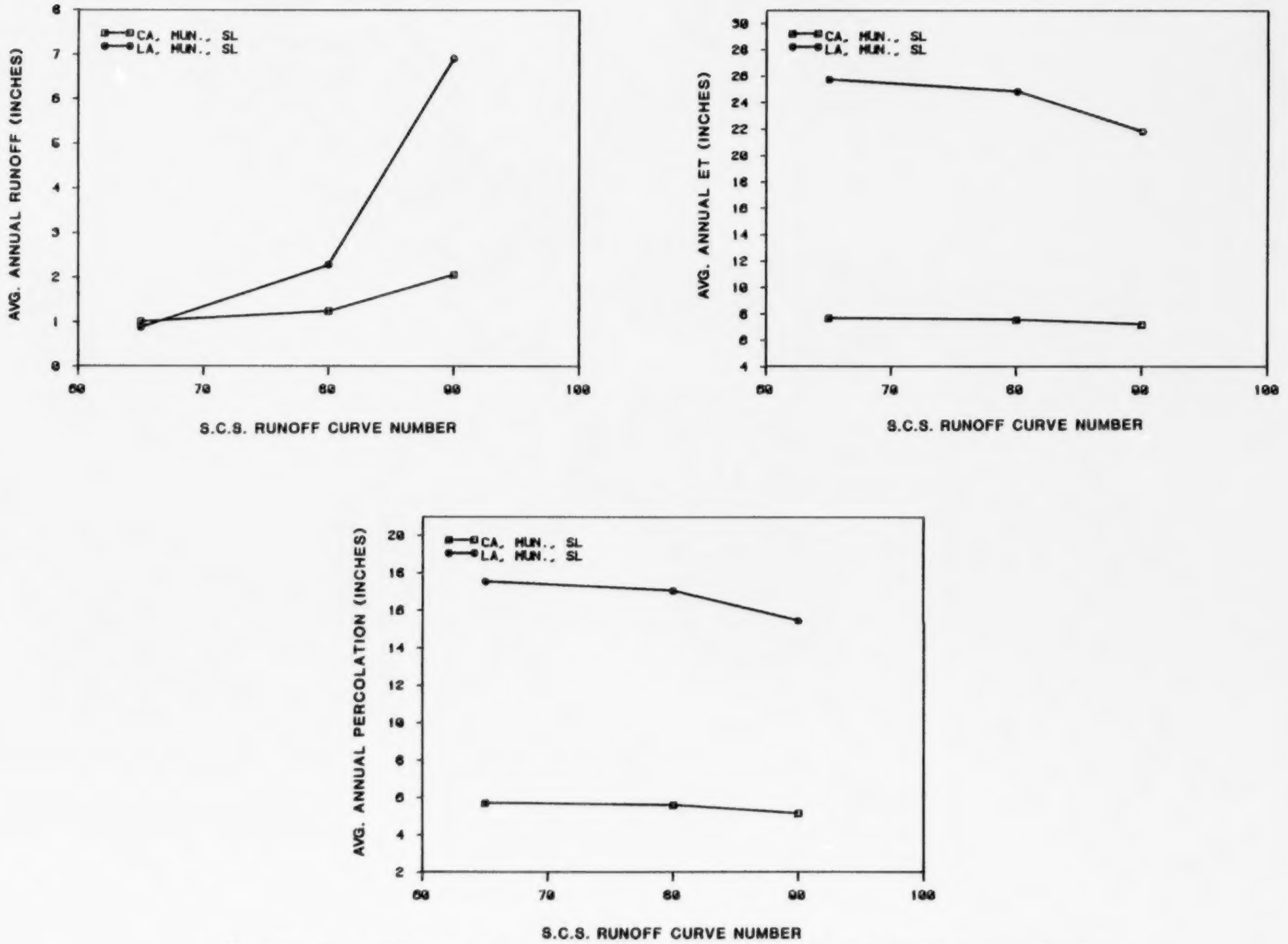


Figure 7. Effect of runoff curve number on municipal cover design. (CA = Santa Maria, California; LA = Shreveport, Louisiana; MUN = municipal design; SL = sandy loam topsoil; SICL = silty clayey loam topsoil)

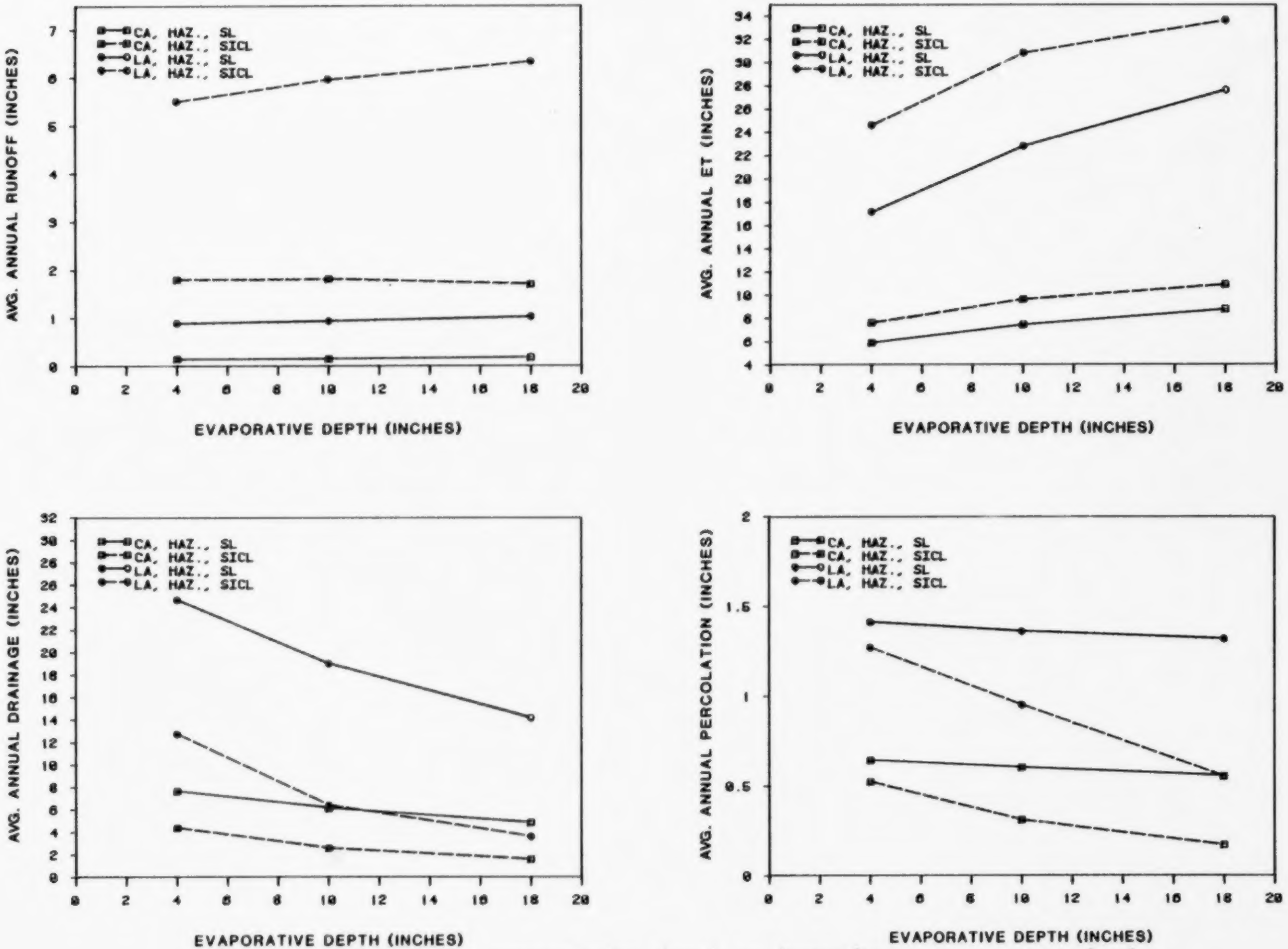


Figure 8. Effect of evaporative depth on hazardous waste cover design. (CA = Santa Maria, California; LA = Shreveport, Louisiana; HAZ = hazardous waste design; SL = sandy loam topsoil; SICL = silty clayey loam topsoil)

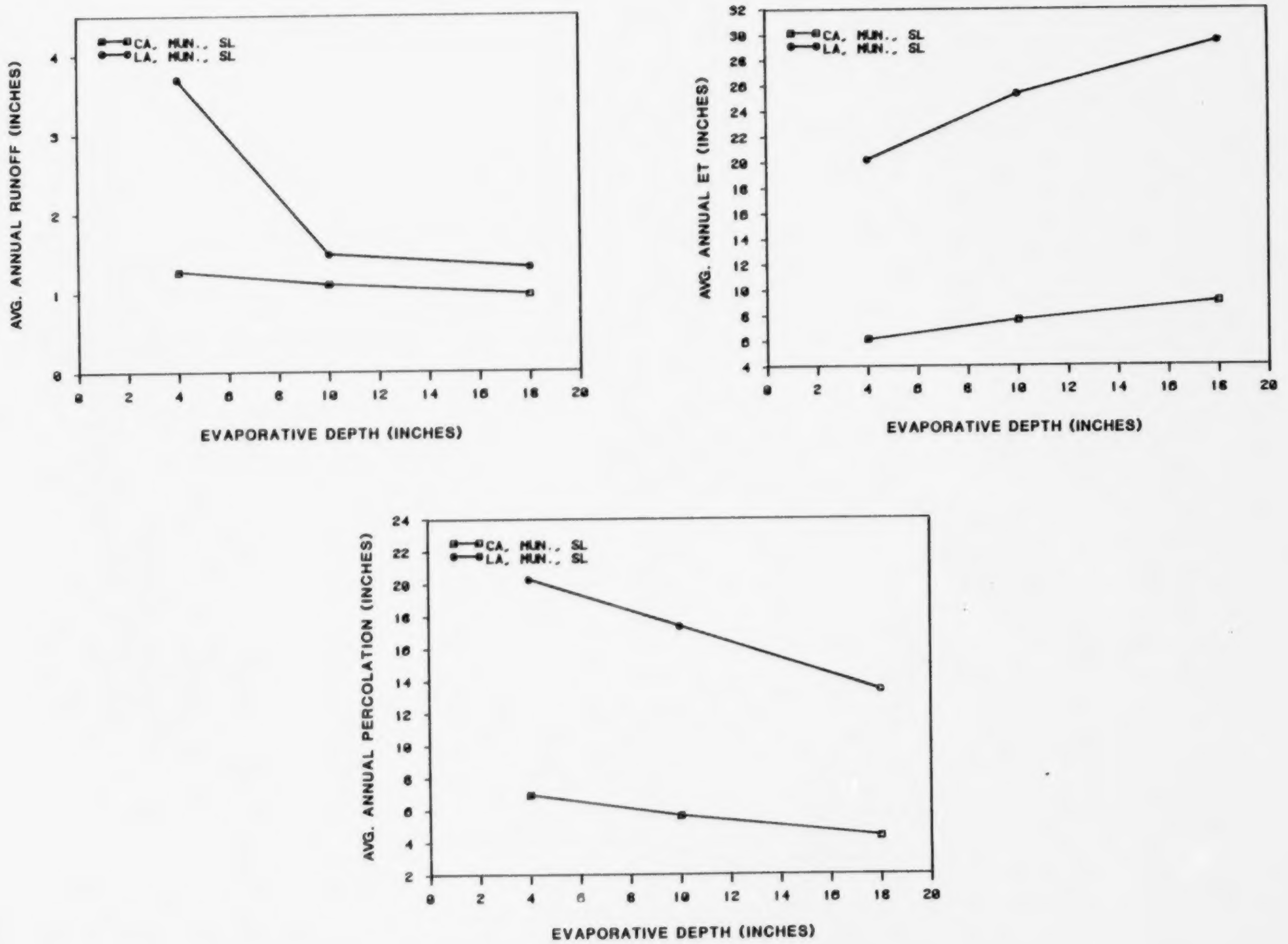


Figure 9. Effect of evaporative depth on municipal cover design. (CA = Santa Maria, California; LA = Shreveport, Louisiana; MUN = municipal design; SL = sandy loam topsoil)

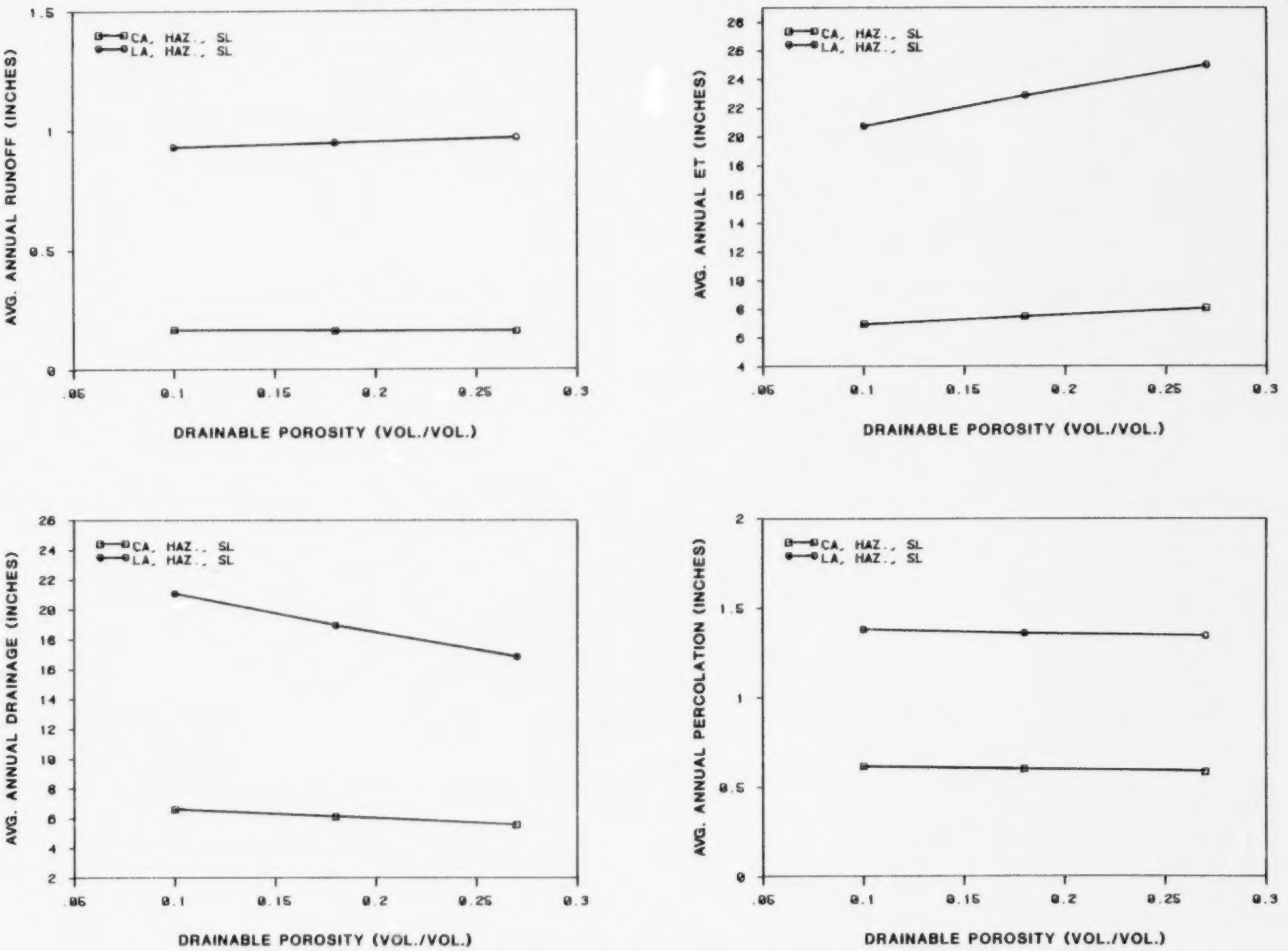


Figure 10. Effect of drainable porosity on hazardous waste cover design. (CA = Santa Maria, California; LA = Shreveport, Louisiana; HAZ = hazardous waste design; SL = sandy loam topsoil)

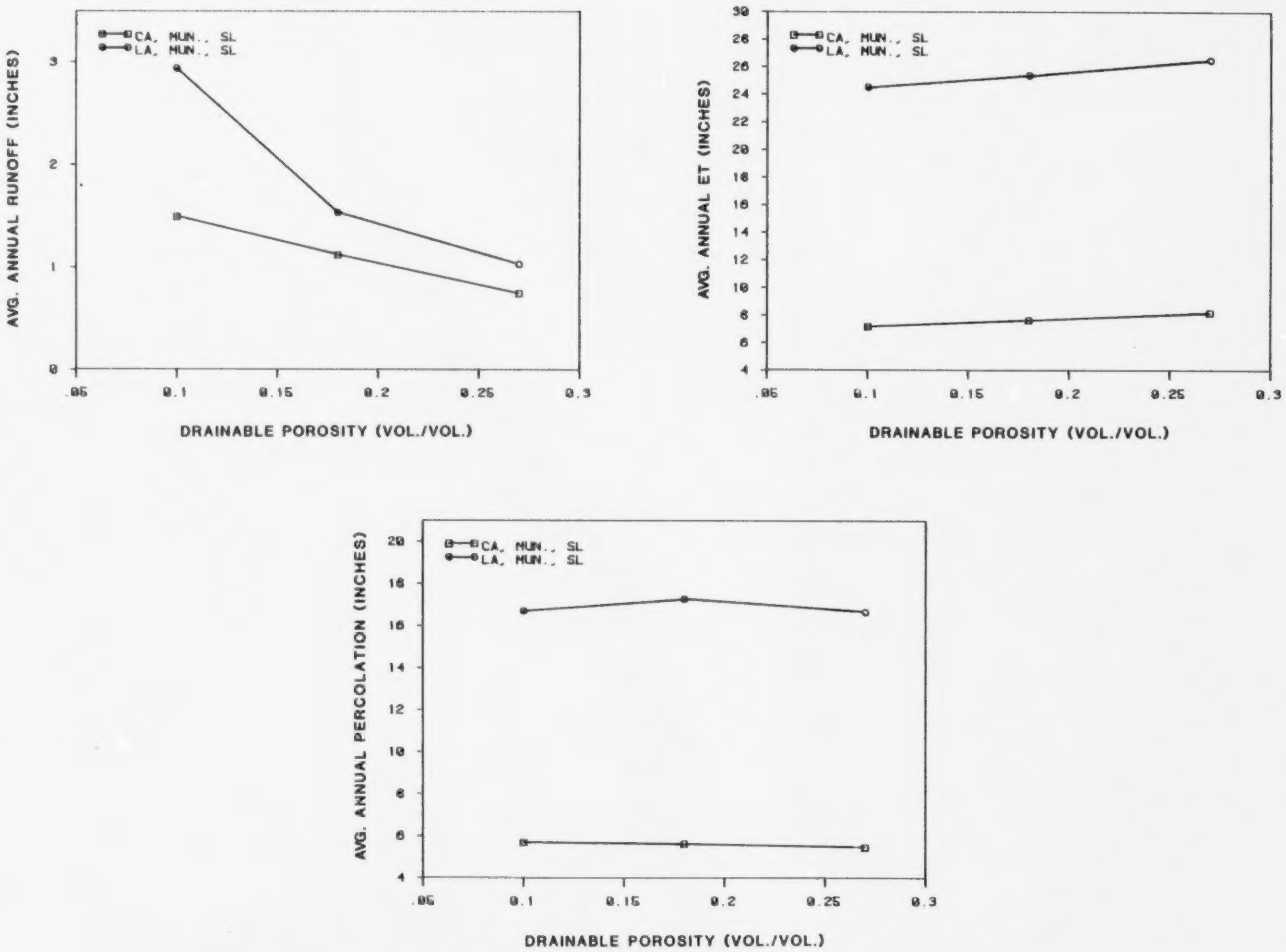


Figure 11. Effect of drainable porosity on municipal cover design. (CA = Santa Maria, California; LA = Shreveport, Louisiana; MUN = municipal design; SL = sandy loam topsoil)

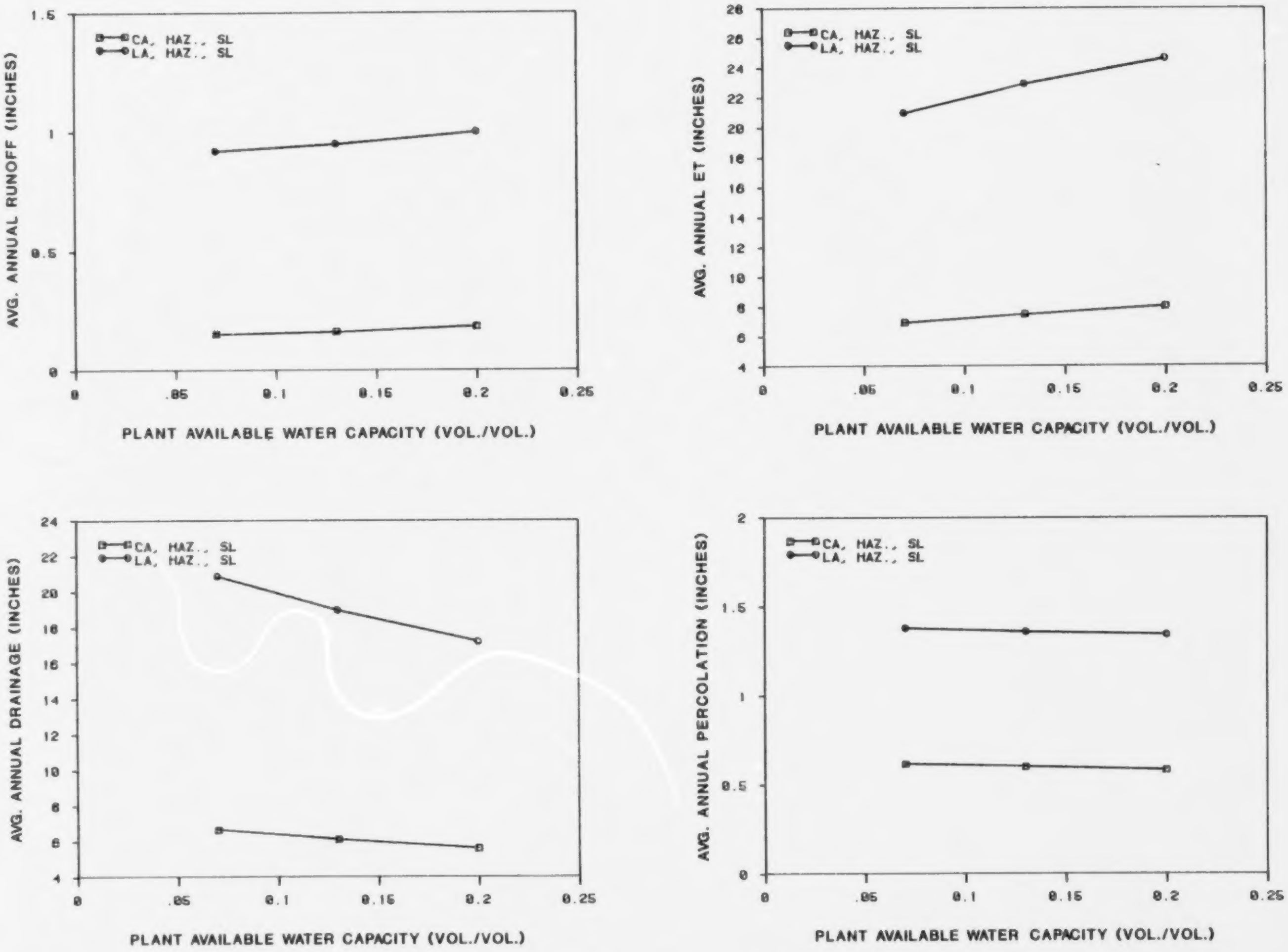


Figure 12. Effect of plant available water on hazardous waste cover design. (CA = Santa Maria, California; LA = Shreveport, Louisiana; HAZ = hazardous waste design; SL = sandy loam topsoil)

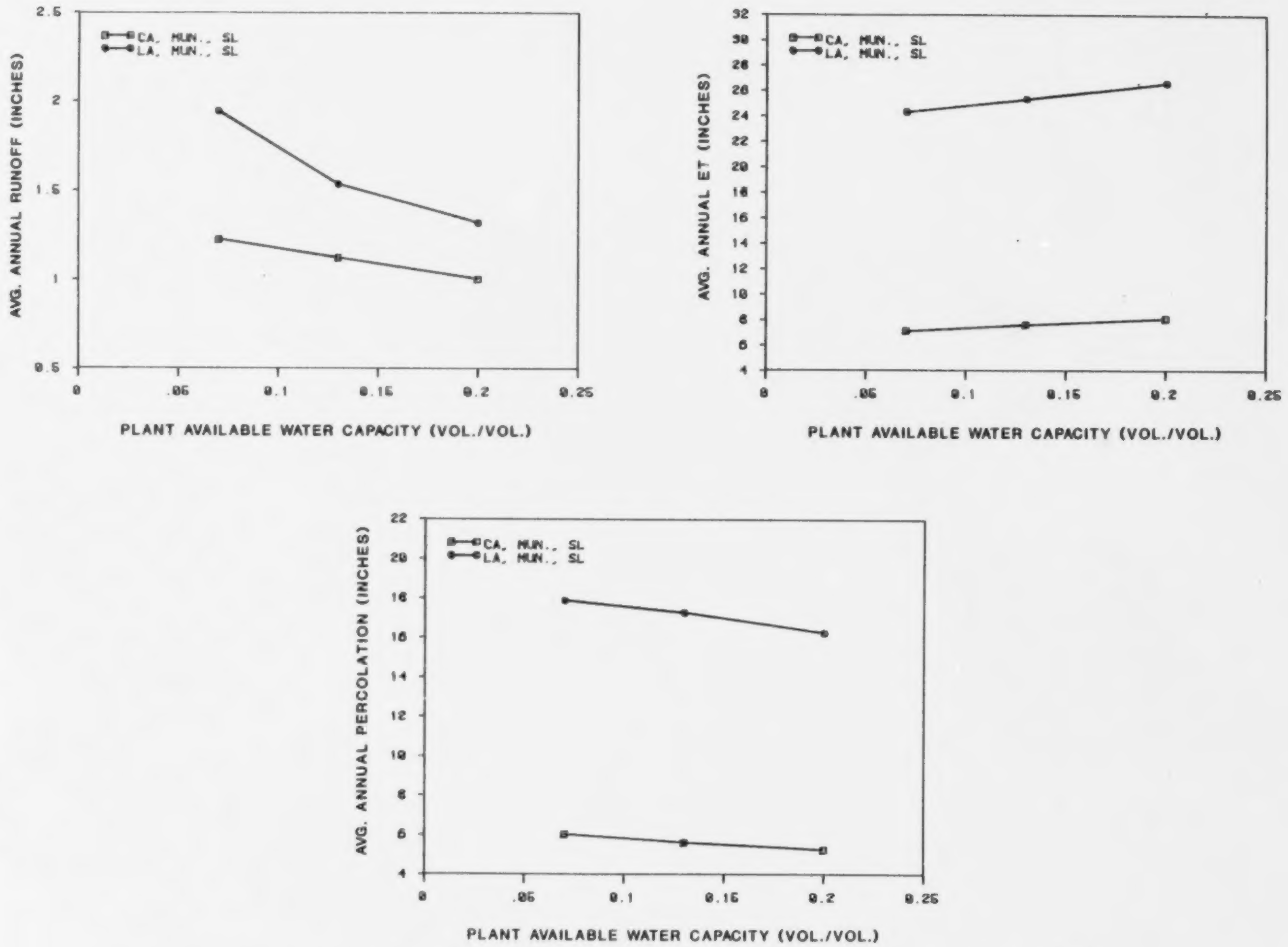


Figure 13. Effect of plant available water on municipal cover design. (CA = Santa Maria, California; LA = Shreveport, Louisiana; MUN = municipal design; SL = sandy loam topsoil)

was 10 inches in all cases. Simulations for the hazardous waste cover design were performed for both soil types, whereas simulations for the municipal design were performed only for sandy loam. The results are presented in Table 4 and Figures 6 and 7.

As expected, an increase in runoff curve number produced an increase in runoff and a decrease in evapotranspiration, lateral leachate drainage, and barrier soil percolation. The percent increase in runoff was less for the municipal design than for the hazardous waste design. This result was due to the higher average moisture content in the topsoil layer of the municipal design caused by the restriction to vertical flow imposed by the barrier soil layer. This limited the infiltration capacity of the topsoil so that excess surface storage accumulated and contributed to the runoff volume. Thus, runoff volume at low curve numbers was higher for the municipal design compared to the hazardous waste design. This effect was not as great at high curve numbers because infiltration for both designs was significantly reduced by the curve number itself.

The effect of location on runoff was difficult to discern from the results presented here. This is due to two unusually large storms at Santa Maria in January and February 1978 which biased the results. For example, in comparing runoff from Santa Maria and Shreveport, one would expect a smaller percentage of precipitation to leave as runoff in Santa Maria due to the higher evapotranspiration demand combined with lower total precipitation and long periods of time between storms. However, for the municipal design simulations at the lower curve numbers, the influence of the two large storms in Santa Maria caused the runoff percentage to exceed that in Shreveport. This would not be the case if the two storms were excluded.

Evaporative Depth--

The evaporative depth was varied from 4 to 18 inches for both sandy loam and silty clayey loam. The runoff curve number was 75 for the sandy loam and 85 for the silty clayey loam. Simulations for the hazardous waste design were performed for both soil types, whereas simulations for the municipal designs were performed only for sandy loam. The results are presented in Table 4 and Figures 8 and 9.

As evaporative depth increased, evapotranspiration increased while lateral drainage and barrier soil percolation decreased; the effect on runoff varied. The interrelationship between these variables in the HELP model is complex and depends on many factors. The increase in evaporative depth allows evapotranspiration to deplete soil moisture from greater depths, generally increasing the total volume of evapotranspiration. However, since the total evapotranspiration demand remains constant, a smaller volume of water depletion occurs per unit depth. Consequently, the antecedent moisture conditions computed by the HELP model could be higher, resulting in larger runoff using the curve number method. The higher moisture content might also reduce the infiltration capacity of the surface soil segment so that excess surface moisture might further increase runoff volume. However, when the time period between storms is sufficiently long, evapotranspiration demand is able to deplete soil moisture to equal levels in either small or large evaporative depths. In this case, runoff volume computed by the HELP model could decrease with increasing evaporative depth since antecedent moisture conditions would remain the same and the increased storage volume in the deeper evaporative zone would increase the infiltration capacity.

The effect of evaporative depth on the volume of lateral drainage and barrier soil percolation is directly related to the composite effect on evapotranspiration and runoff. In the examples chosen for Table 4 and Figures 8 and 9, the increase in evapotranspiration with increased evaporative depth was greater than any increase in infiltration; therefore, lateral drainage and barrier soil percolation always decreased.

An increase in evaporative depth caused an increase in infiltration for the municipal design compared to a slight decrease for the hazardous waste design. This difference relates to the different mechanisms controlling infiltration in these two cases. For the municipal design, the hydraulic conductivity of the clay barrier soil was much less than the sandy loam topsoil. Therefore, infiltration tended to saturate the topsoil layer, and the total volume of infiltration was dependent primarily on the volume of empty storage available in this layer. A larger evaporative depth increased the potential for a larger volume of empty storage and thus for more infiltration. For the hazardous waste design, the lateral drainage layer generally maintained a free outfall condition at the topsoil/lateral drainage layer interface. Infiltration was then controlled primarily by the hydraulic conductivity of the topsoil and the empty storage volume in the top segment of the subprofile. As explained above, this condition could result in either an increase or decrease in infiltration with an increase in evaporative depth.

Drainable Porosity--

This term is defined as the difference between porosity and field capacity; that is, the amount of water that could be vertically drained from a saturated soil by gravity. Values ranged from 0.100 to 0.270 in this study. These values represent the volume of moisture storage capacity in excess of field capacity, divided by the bulk volume of soil including voids. Values for field capacity and wilting point remained constant at 0.263 and 0.133, respectively. Only sandy loam soil was considered. The evaporative depth was 10 inches, and the runoff curve number was 75. Both hazardous waste and municipal designs were simulated. The results are presented in Table 5 and Figures 10 and 11.

An increase in drainable porosity increases the moisture storage volume above field capacity. Therefore, more water can be made available during vertical drainage for evapotranspiration. An increase in drainable porosity (with constant field capacity) will also decrease the height to which ponded water can rise into the top soil layer. The net result is shown to increase the volume of evapotranspiration and decrease the volume of lateral drainage and barrier soil percolation in Table 5 and Figures 10 and 11. However, the effect of increased drainable porosity on runoff is varied. For the hazardous waste design, runoff decreased slightly at Santa Maria and increased slightly at Shreveport. For the municipal design, runoff decreased significantly at both locations since the relative soil moisture is lower and the available storage is greater. At Santa Maria, where evapotranspiration demand is high and precipitation is low, the moisture storage volume above field capacity tends to remain empty. An increase in this storage volume results in larger empty storage available for infiltration. Combined with low antecedent moisture conditions due to climate, the increased drainable porosity tends to reduce runoff. At Shreveport, where unsatisfied evapotranspiration demand is lower and precipitation is higher, the moisture storage volume above field capacity remains partially filled for longer periods of time compared to Santa Maria. An increase in this storage volume without an accompanying increase in hydraulic conductivity lengthens further the time required to drain the moisture to field capacity. Therefore at Shreveport, an increase in drainable porosity increased the potential for higher antecedent moisture conditions and thus higher runoff, which is shown in the simulation results for the hazardous waste design at Shreveport. For the municipal design, infiltration is controlled to a larger extent by the available storage volume in the top soil rather than its hydraulic conductivity, as explained earlier. Thus, an increase in drainable porosity resulted in greater infiltration and less runoff for both municipal designs.

Plant Available Water Capacity--

This term is defined as the difference between field capacity and wilting point, or the amount of water available for plant uptake after vertical drainage by gravity has ceased. Values ranged from 0.070 to 0.200 in this analysis. These values represent the volume of moisture storage capacity between wilting point and field capacity, divided by the bulk volume of soil including voids. The values for wilting point and drainable porosity remained constant at 0.133 and 0.180, respectively. Only sandy loam soil was considered. The evaporative depth was 10 inches, and the runoff curve number was 75. Both hazardous waste and municipal designs were simulated. The results are presented in Table 5 and Figures 12 and 13.

As plant available water increases, a greater volume of water is available for evapotranspiration after vertical drainage has ceased. This results in larger evapotranspiration losses as indicated in Table 5 and Figures 12 and 13. However, it also results in an increased moisture content at field capacity and therefore a greater potential for higher antecedent moisture conditions. In the hazardous waste designs, this effect was apparently influencing the small increase in runoff with increased plant available water capacity. Runoff decreased for the municipal designs so that, as before, available storage volume appeared to be controlling infiltration in these cases. From Table 5 it is seen that the increases in evapotranspiration were great enough to offset any increases in infiltration; therefore, leachate drainage and barrier soil percolation also decreased.

Summary of Sensitivity Analysis for Landfill Cover

The interrelationship between parameters influencing the hydrologic performance of a landfill cover in the HELP model is complex. It is difficult to isolate one parameter and exactly predict its effect on the water balance without first placing restrictions on the values of the remaining parameters. With this qualification in mind, the following general summary statements are made.

The primary importance of the topsoil depth or thickness is in controlling the extent or existence of overlap between the evaporative depth and the head in the lateral drainage layer. Surface vegetation has a significant effect on evapotranspiration from soils with long flow-through travel times (low hydraulic conductivity) and large plant available water capacities; otherwise, the effect of vegetation on evapotranspiration is small. The general influence of surface vegetation on lateral drainage and barrier soil percolation is difficult to predict outside the context of an individual cover design. Clayey soils produce greater runoff and evapotranspiration, and less lateral drainage and barrier soil percolation. Simulations of landfills in colder climates and in areas of lower solar radiation are likely to show less evapotranspiration and greater lateral drainage and barrier soil percolation. An increase in the runoff curve number will increase runoff and decrease evapotranspiration, lateral drainage, and barrier soil percolation. As evaporative depth, drainable porosity or plant available water increase, evapotranspiration tends to increase while lateral drainage and barrier soil percolation tend to decrease; the effect on runoff is varied.

LATERAL DRAINAGE AND BARRIER SOIL PERCOLATION

This analysis examines how lateral drainage and barrier soil percolation in the HELP model are affected by the slope, drainage length, and saturated hydraulic conductivity of the lateral drainage layer, K_D, and by the saturated hydraulic conductivity of the barrier soil layer, K_P. Two types of vertical inflows to the lateral drainage layer were considered. First, an inflow rate of 50 inches/year was used to represent infiltration at an open landfill. This inflow was distributed in time according to actual rainfall patterns at Shreveport, LA. Second, an inflow rate of 8 inches/year uniformly distributed in time was used to represent infiltration at a covered landfill. In the discussion that follows, the hydraulic conductivities are first investigated by holding the slope and drainage length constant. Then, the slope and drainage length are examined by holding the hydraulic conductivities constant. In all cases, the thickness of the lateral drainage layer was greater than the maximum head, and the thickness of the barrier soil layer, T_c, was 24 inches.

The equation used in the HELP model to compute the barrier soil percolation rate, Q_P, is Equation 18 where the average thickness of lateral flow, $\bar{y}$, is used for the total head above the barrier soil layer, TH, resulting in

$$Q_P = K_P \frac{\bar{y} + T_c}{T_c} \tag{26}$$

The equation used to compute the lateral drainage rate, Q_D, is Equation 25. The two equations are solved simultaneously to compute Q_P, Q_D, and $\bar{y}$.

Hydraulic Conductivities

The combinations of K_D and K_P values used in this analysis are listed in Table 6 along with resulting average annual volumes of lateral drainage and barrier soil percolation expressed as a percentage of annual inflow. Values

TABLE 6. SENSITIVITY OF LINER/DRAIN SYSTEM PERFORMANCE TO HYDRAULIC CONDUCTIVITY OF LATERAL DRAINAGE LAYER AND BARRIER SOIL LAYER

Annual** Infilt. (in.)	Hyd. Cond. Lat. Drng. K_D (cm/sec)	Hyd. Cond. Barrier Soil K_P (cm/sec)	$\frac{K_D}{K_P}$	Avg. Annual Vol.* (% Inflow)		Max Head in Lat. Drng Layer (in.)
				Lat.† Drng.	Barrier†† Soil Perc.	
50	10^{-1}	10^{-5}	10^4	26.16	73.84	6.3
50	10^{-1}	10^{-6}	10^5	81.44	18.56	7.9
50	10^{-1}	10^{-7}	10^6	97.44	2.56	8.1
50	10^{-2}	10^{-6}	10^4	67.35	32.65	22.9
50	10^{-2}	10^{-7}	10^5	96.36	3.64	24.8
50	10^{-3}	10^{-6}	10^3	46.79	53.21	46.4
50	10^{-3}	10^{-7}	10^4	93.18	6.82	60.6
50	10^{-3}	10^{-8}	10^5	99.30	0.70	62.0
8	10^{-1}	10^{-5}	10^4	0.58	99.42	<0.1
8	10^{-1}	10^{-6}	10^5	5.55	94.45	<0.1
8	10^{-1}	10^{-7}	10^6	84.37	15.63	0.2
8	10^{-2}	10^{-6}	10^4	0.58	99.42	<0.1
8	10^{-2}	10^{-7}	10^5	83.56	16.40	1.4
8	10^{-3}	10^{-6}	10^3	0.06	99.94	<0.1
8	10^{-3}	10^{-7}	10^4	77.60	21.97	10.1
8	10^{-3}	10^{-8}	10^5	97.22	2.32	12.1

---

* Change in storage is not included in this table; therefore, the water balance components shown do not always sum to 100.0%.

** Value of 50 in./year represents inflow through an open landfill; the temporal distribution is based on rainfall records for Shreveport, LA. Value of 8 in./year represents inflow through landfill cover; the temporal distribution is uniform throughout the year.

† Slope = 3%; drainage length = 75 ft; porosity = 0.351 vol/vol; field capacity = 0.174 vol/vol.

†† For 24-in. barrier soil layer.

of K_D ranged from 10^{-3} to 10^{-1} cm/sec while those of K_p ranged from 10^{-8} to 10^{-5} cm/sec. The slope was 3 percent, and the drainage length was 75 feet.

For the large inflows (50 inches/year), only three cases produced barrier soil percolation volumes less than 5 percent of the inflow, all with barrier soil hydraulic conductivities of 10^{-7} cm/sec or less: $K_D = 10^{-1}$ and $K_p = 10^{-7}$ cm/sec; $K_D = 10^{-2}$ and $K_p = 10^{-7}$ cm/sec; and $K_D = 10^{-3}$ and $K_p = 10^{-8}$ cm/sec. Only the case with $K_p = 10^{-8}$ restricted percolation to less than 1 inch/year. For the small inflows (8 inches/year), only one case produced barrier soil percolation volumes less than 5 percent of the inflow: $K_D = 10^{-3}$ and $K_p = 10^{-8}$ cm/sec. This was the only case which restricted percolation to less than 1 inch/year.

Figure 14 shows how the hydraulic conductivities affected lateral drainage and barrier soil percolation. In particular, the curves for the small inflows show that almost all inflow leaves as percolation at K_p values of 10^{-6} cm/sec and greater. This is consistent with Equations 25 and 26 which indicate that as $\bar{y}$ approaches zero, the percolation rate approaches the hydraulic conductivity of the barrier soil while the lateral drainage rate approaches zero.

The effect is also seen in Figure 15 which relates the K_D/K_p ratio to lateral drainage and barrier soil percolation. The curves represent steady-state analytical solutions to Equations 25 and 26, while the data points represent results of the HELP model simulations for the 50- and 8-inches/year inflows. The trend is for percolation to dominate as heads decrease.

Since the inflow rate of 8 inches/year was applied uniformly in time, the maximum heads listed in Table 6 for these inflows should approximate the steady-state values of $\bar{y}$ in Figure 15. A comparison of these maximum heads computed by the HELP model to the position of the data points in the figure indicates that the two are consistent.

Since the HELP model does not print values of $\bar{y}$, heads for the 50-inches/year inflows cannot be compared in the same manner. However, in each case the maximum head for these larger inflows is greater than the corresponding $\bar{y}$ on Figure 15.

Slope and Drainage Length

The combinations of slope and drainage length used in this analysis are listed in Table 7 along with resulting average annual volumes of lateral drainage and barrier soil percolation expressed as a percentage of annual inflow. The table also contains the resulting maximum heads above the barrier soil layer. The slope ranged from 0.01 to 0.09 (1 to 9 percent) while the drainage length ranged from 25 to 225 ft. The hydraulic conductivities of the lateral drainage and barrier soil layers were 10^{-2} and 10^{-7} cm/sec, respectively. The product of αL and the ratio of L/α ranged from 0.25 to 6.75 ft and 280 ft to 22,500 ft, respectively.

The term αL is a measure of head above the drain resulting from the sloped barrier soil layer. While an increase in head generally increases the

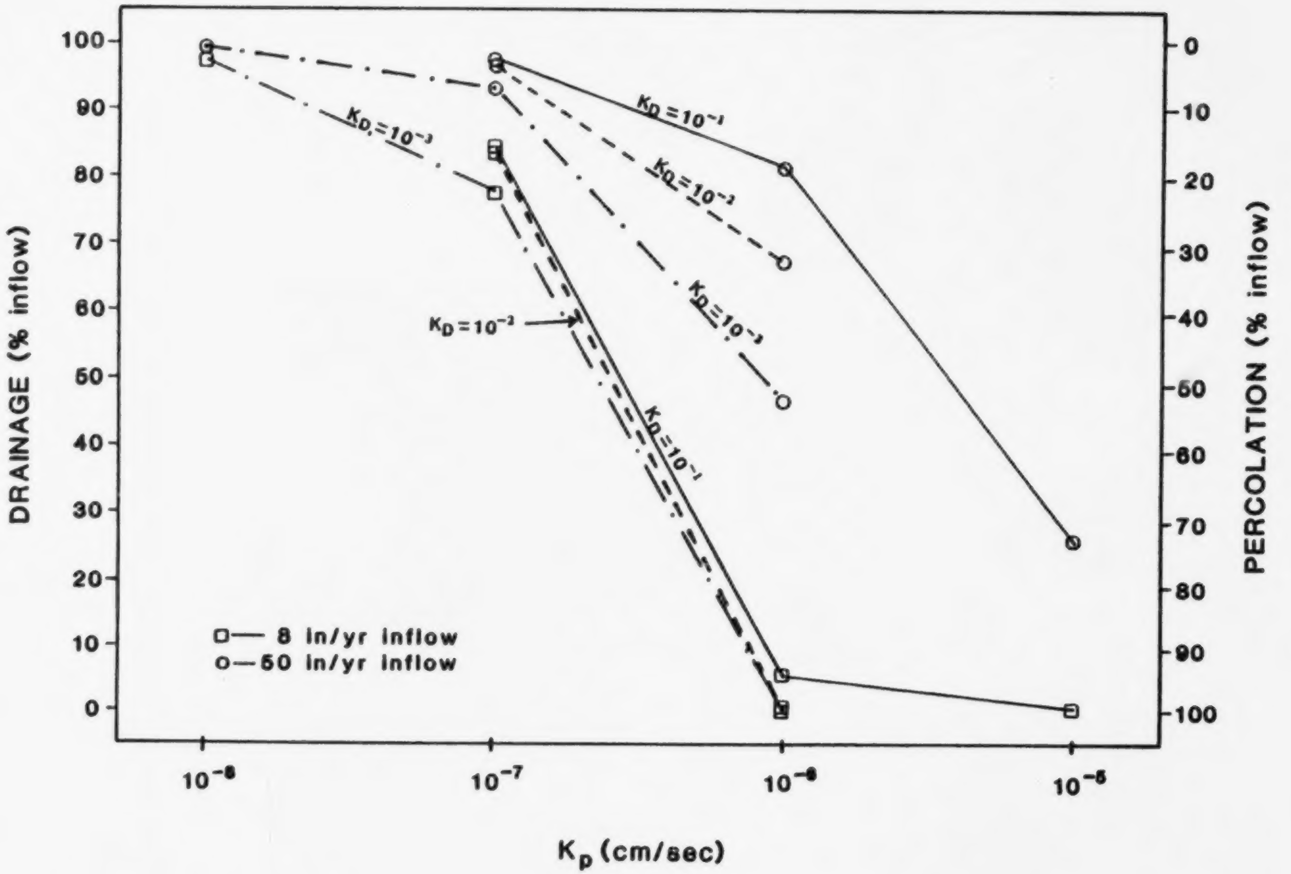


Figure 14. Effect of K_D and K_p on lateral drainage and barrier soil percolation (drainage slope = 3%; drainage length = 75 ft; thickness of barrier soil layer = 24 in.).

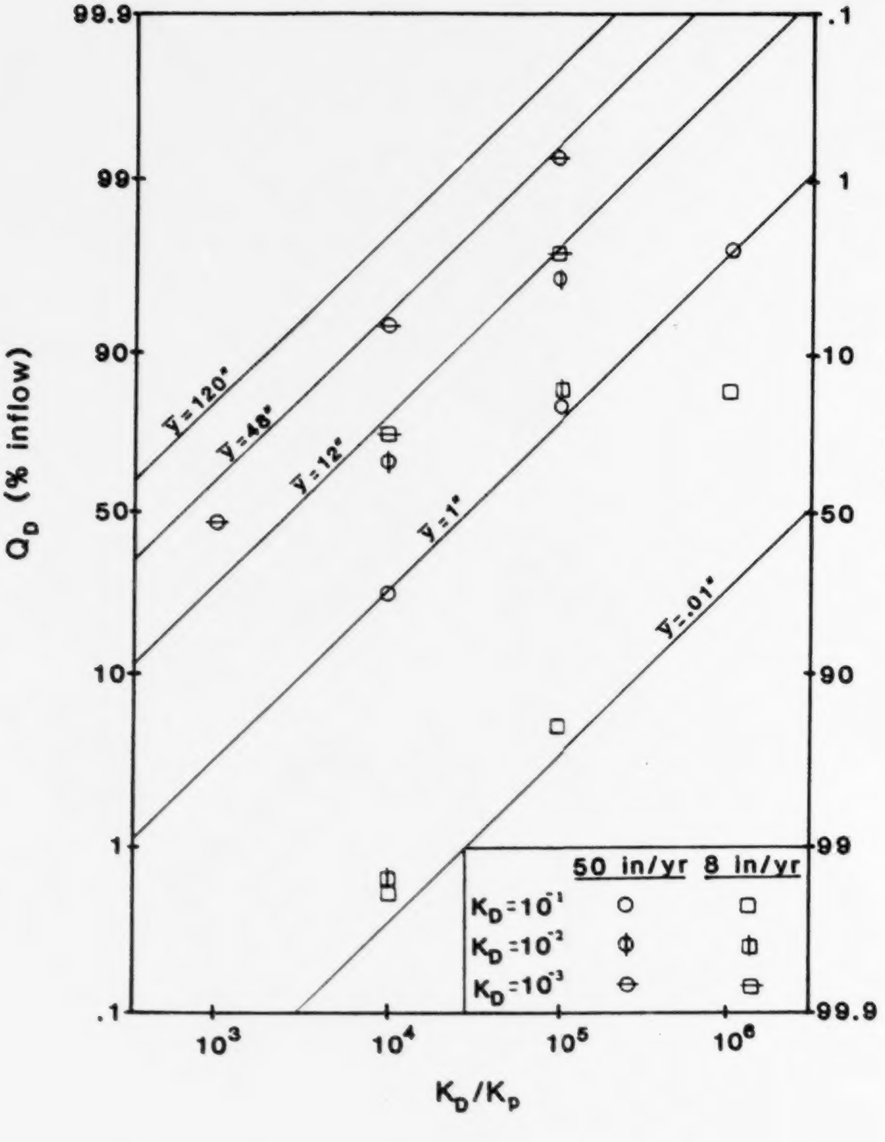


Figure 15. Effect of K_D/K_p ratio on lateral drainage and barrier soil percolation (drainage slope = 3%; drainage length = 75 ft; thickness of barrier soil layer = 24 in.).

TABLE 7. SENSITIVITY OF LINER/DRAIN SYSTEM PERFORMANCE TO LATERAL DRAINAGE SLOPE AND LENGTH

					Avg. Annual Vol.* (% Inflow)		
Annual** Infilt. (in.)	Slope α (ft/ft)	Length L (ft)	αL (ft)	L/α (ft)	Lat.† Drng.	Barrier†† Soil Perc.	Max. Head in Lat. Drng. Layer (in.)
50	0.01	25	0.25	2500	96.71	3.29	13.8
50	0.01	75	0.75	7500	95.89	4.11	29.7
50	0.01	225	2.25	22500	93.42	6.57	58.2
50	0.03	25	0.75	830	96.85	3.15	12.3
50	0.03	75	2.25	2500	96.36	3.64	24.8
50	0.03	225	6.75	7500	95.10	4.90	42.3
50	0.09	25	2.25	280	97.37	2.63	8.5
50	0.09	75	6.75	830	96.86	3.13	16.2
8	0.01	25	0.25	2500	83.71	16.27	1.2
8	0.01	75	0.75	7500	82.23	17.71	3.4
8	0.01	225	2.25	22500	78.21	21.49	9.4
8	0.03	25	0.75	830	84.16	15.84	0.5
8	0.03	75	2.25	2500	83.55	16.41	1.1
8	0.03	225	6.75	7500	82.20	17.72	3.5
8	0.09	25	2.25	280	84.35	15.65	0.2
8	0.09	75	6.75	830	84.22	15.77	0.4

---

* Change in storage is not included in this table; therefore, the water balance components shown here do not always sum to 100.0 percent.

** Value of 50 in./year represents inflow through an open landfill; the temporal distribution is based on rainfall records for Shreveport, LA. Value of 8 in./year represents inflow through landfill cover; the temporal distribution is uniform throughout the year.

† Hydraulic conductivity = 10^{-2} cm/sec; porosity = 0.351 vol/vol; field capacity = 0.174 vol/vol.

†† For 24-in. barrier soil layer; hydraulic conductivity = 10^{-7} cm/sec.

lateral drainage, an increase in αL resulting from an increase in drainage length does not increase lateral drainage because the lateral drainage is also a function of $1/L^2$, as seen in Equation 25. An increase in αL resulting from an increase in slope does increase the lateral drainage. At constant values of αL, lateral drainage decreases as the drainage length increases.

For a low, uniform infiltration rate, y_o remains small so that from Equation 21, h_o is approximately equal to αL. Therefore using Equations 20, 21 and 22, the steady-state average head in the lateral drainage layer was linearly related to L/α as follows:

$$\bar{y} \approx \frac{\left(\frac{Q_D}{K_D}\right)\left(\frac{L}{\alpha}\right)}{1.02 + 0.0041\ \alpha L} \tag{27}$$

where $\bar{y}$ and L are in inches and Q_D and K_D have the same units. The results for the 8-inches/year infiltration rate listed in Table 7 are plotted in Figure 16 to show this relationship. With unsteady infiltration the maximum average head in the lateral drainage layer was also a function of L/α, but the relationship was no longer linear due to the storage available in the lateral drainage layer.

Percolation through barrier soil increases with drainage length and decreases with slope because the lateral drainage rate decreases. As a result of the decrease in drainage rate, the head increases and is maintained at greater depths for longer periods of time. Consequently, the percolation increases as predicted by Equation 26. Since percolation is a function of $\bar{y}$ and $\bar{y}$ is a function of L/α as shown in Equation 27, percolation increases linearly with increases in L/α. The percolation results listed in Table 7 are plotted in Figure 17 to show the effect of L/α on percolation.

Lateral drainage increases with slope and decreases with drainage length in the opposite manner that percolation changes. The decrease in the net lateral drainage is a result of the increase in percolation. In the absence of significant increases in percolation, the head increases to yield only small changes in the lateral drainage rate when large changes in slopes and drainage lengths are used.

Summary of Sensitivity Analysis for Lateral Drainage and Percolation

The sensitivity analysis shows that the ratio of lateral drainage to percolation is a positive function of the ratio of K_D/K_P and the average head above the liner. However, the average head is a function of Q_D/K_D and L/α. The quantity of lateral drainage, and therefore also the average head, is in turn a function of the infiltration. Therefore, the ratio of lateral drainage to percolation increases with increases in infiltration, and the ratio of K_D/K_P for a given drain and liner design. The ratio of lateral drainage to percolation for a given ratio of K_D/K_P increases with increases in infiltration and decreases in L/α. The percolation and average head above the liner are positive functions of the term L/α.

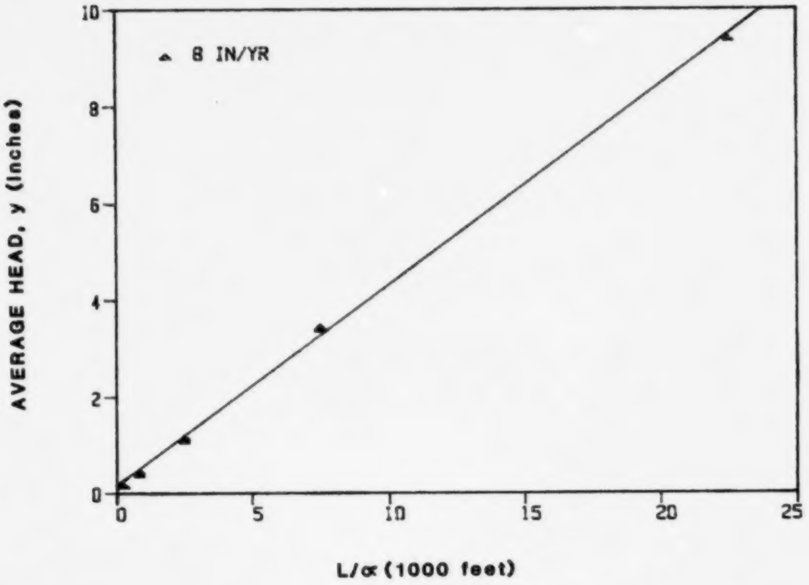


Figure 16. Effect of L/α on the steady-state and maximum average head above the liner.

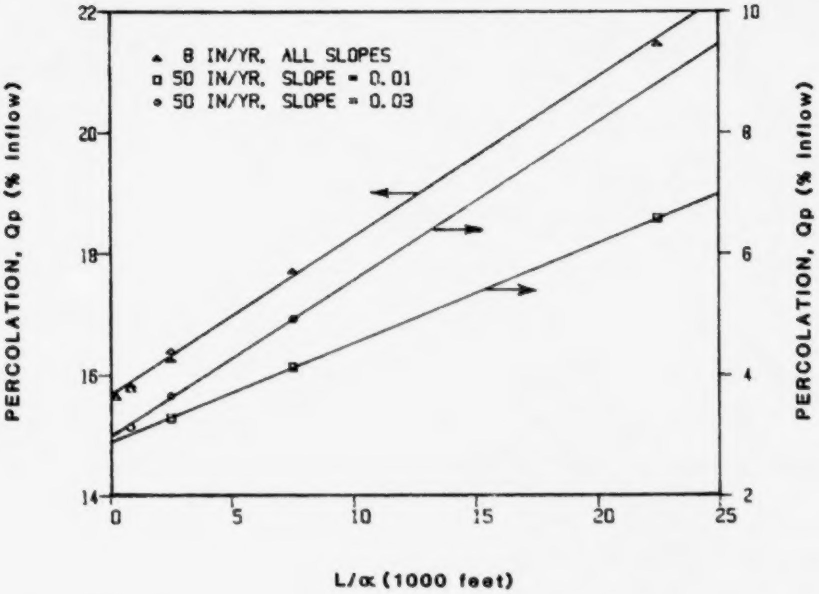


Figure 17. Effect of L/α on percolation.

SECTION 5

REVIEW OF LANDFILL DESIGN REGULATION AND GUIDANCE

This section evaluates the Resource Conservation and Recovery Act (RCRA) landfill design regulation, as amended by the Hazardous and Solid Waste Amendments of 1984 (HSWA) (10), and Minimum Technology Guidance (MTG) (11) based on the results of the laboratory and field verification studies and the sensitivity analysis. This evaluation examines whether the guidance is practicable and achieves its objectives in the best practicable manner. The evaluation examined guidance on final covers, liners and leachate detection, collection and removal systems. Evaluation of the final cover guidance included effects of vegetation, vegetated cover soil thickness, drainage layer design and liner design. Evaluation of liners included effects of liner thickness and hydraulic conductivity. Evaluation of leachate detection, collection and removal systems examined hydraulic conductivity, slope and maximum drainage length of the drainage layer. The goal of the designs is to minimize the potential percolation through the liner at the base of the landfill.

REGULATION

New and laterally expanded RCRA landfills must have a double liner system that is designed, constructed, and installed to prevent any migration of wastes out of the landfill and into or out of the space between the two liners. The liners must be constructed of materials that prevent wastes from passing out of the liners during the operating period of the facility. A leak detection system must be designed, constructed, maintained, and operated between the liners to detect any migration of liquid into the space between the liners. The landfill must have a leachate collection and removal system above the top liner to ensure that the leachate depth over the liner does not exceed 30 cm (1 foot) (10). The Regional Administrator will specify design and operating conditions in the permit to ensure that the leachate depth over the liner does not exceed 30 cm (1 foot). The owner or operator must design, construct, operate, and maintain a runon control system capable of preventing flow on to the active portion of the landfill during peak discharge from at least a 25-year storm and a runoff management system to collect and control at least the water volume resulting from a 24-hour, 25-year storm. The Regional Administrator will specify in the permit all design and operating practices that are necessary to ensure that the requirements of this regulation are satisfied (10).

At final closure of the landfill or any cell, the owner or operator must cover the landfill or cell. The cover must be designed and constructed to provide long-term minimization of migration of liquids through the closed landfill, function with minimum maintenance, promote drainage and minimize erosion of the cover, accommodate settling and subsidence, and have a permeability less than or equal to the permeability of any bottom liner system.

GUIDANCE

RCRA Minimum Technology Guidance on Double Liner Systems (11) specifies designs for liners, and leachate detection, collection and removal systems. The RCRA Guidance Document for Landfill Design (12) specifies designs for final covers. The guidance for liners recommends that the liners be constructed wholly above the seasonal high water table. The double liner system should consist of a primary leachate collection and removal system; a flexible membrane liner (FML) for the top liner; a secondary leachate collection and removal system; and a low permeability soil liner or a composite (FML plus low permeability soil) for the bottom liner.

The flexible membrane liner should be chemically resistant to the waste and leachate. The FML should have a thickness of at least 30 mils; greater thicknesses are necessary if the liner will be exposed to weather for an extended period or unusual stresses during installation and operation. The FML should be protected from damage from above and below by at least 12 inches of bedding material that is no coarser than sand (soil type SP using the Unified Soil Classification System). The bedding material must be smooth and free of rock, fractured stone, debris, cobbles, rubbish, and roots (11).

The low permeability soil liner should have an in-place saturated hydraulic conductivity not more than 1×10^{-7} cm/sec and a thickness of not less than 90 cm (3 feet). The soil must be free of large clods, rock, fractured stone, debris, cobbles, rubbish, and roots that would increase hydraulic conductivity or serve to promote preferential leachate flow paths (11).

The primary leachate collection and removal system should have at least a 30-cm (1 foot) chemically resistant drainage layer with a hydraulic conductivity not less than 1×10^{-2} cm/sec and a minimum bottom slope of 2 percent. A graded granular or synthetic fabric filter should be placed above the drainage layer to prevent clogging. A drainage pipe system of appropriate size and spacing and a sump pump should be installed to efficiently remove leachate from the drainage layer. The leachate collection system should cover the entire bottom and sidewalls of the landfill unit (11).

The secondary leachate collection and removal system should permit rapid detection, collection, and removal of any migration of liquid into the space between the liners. The drainage layer should be chemically resistant to the waste and leachate, have a hydraulic conductivity not less than 1×10^{-2} cm/sec and a minimum bottom slope of 2 percent. A drainage pipe system of appropriate size and spacing and a sump pump should be installed to efficiently remove leachate from the drainage layer. The leachate collection system should cover all areas between the double liners likely to be exposed to waste and leachate (11).

The final cover should have a vegetated top cover, a middle drainage layer and a liner as a minimum. The vegetated top cover should be at least 60 cm (2 feet) thick and support persistent, shallow-rooted, erosion-controlling vegetation. The cover should have a slope of 3 to 5 percent to promote runoff collection without causing excessive erosion. The drainage layer should be at least 30 cm (1 foot) thick with a saturated hydraulic conductivity of not less than 1 x 10^{-3} cm/sec and have a bottom slope of at least 2 percent. Lateral drainage should be collected from the drainage layer. The liner should be composed of at least a 20-mil synthetic membrane overlying a 60-cm (2-foot) layer of compacted clay soil having a hydraulic conductivity of not more than 1 x 10^{-7} cm/sec (12).

EVALUATION AND RECOMMENDATIONS

Liner Systems

Results of the studies show that soil (clay) liners restrict percolation and migration of liquids from landfills but do not prevent it. Small quantities of percolation occur even with an overdesigned leachate collection and removal system and a very low permeability soil liner according to the HELP model simulations. Therefore, the use of synthetic membranes in conjunction with soil liners appears prudent. Field data were not available to verify this prediction.

Two design specifications are used for soil liners: thickness and saturated hydraulic conductivity. Percolation is primarily controlled by the saturated hydraulic conductivity and not thickness. Very large changes in percolation rates can be obtained by the materials and construction methods selected for the soil liner while only small improvements can be achieved by using very thick liners. The thickness of the liner should be controlled by the requirements for uniformity, physical strength and subsidence. A thickness of 3 feet should be more than adequate to meet these requirements.

Based on field observations, the MTG (11) recommending that soil liners have saturated hydraulic conductivities not more than 1 x 10^{-7} cm/sec is very reasonable and practicable. Most landfill cells used in this study had hydraulic conductivities that were very close to the guidance.

Use of low permeability soil for the bottom liner instead of a composite liner may defeat the leak detection capabilities of the secondary leachate collection and removal system. In addition, it would consequently violate the intent of the HSWA (10) to prevent migration of any hazardous constituents from the facility and the design criterion of the MTG (11) to minimize the migration of any hazardous constituent through the bottom soil liner. The HELP model predicts that small leakage from a FML would all pass through the soil liner without detection if the leakage rate is less than the saturated hydraulic conductivity of the soil liner. This would occur because sufficient head would not build up in the secondary leachate collection and removal system to divert the leakage to the sump.

Leachate Collection and Removal System

By regulation (10), the leachate depth over the liner must not exceed 30 cm (1 foot), but based on HELP model simulations the existing technical guidance does not appear to satisfy this during the active life of a landfill cell. The capability to maintain the leachate depth below 30 cm (1 foot) under all conditions except rare storms requires extraordinary designs. The drainage layer must have very high saturated hydraulic conductivity, not less than 2×10^{-2} cm/sec. The slope of the drainage layer base must be at least 10 percent, and the drain pipe spacing should be not more than 50 feet. With this design the system should be able to accommodate infiltration rates up to 4 inches/day (a 1-year return period event in some regions).

Saturated hydraulic conductivity of the drainage media, slope of the drainage layer base and drain spacing are the only design parameters of the leachate collection and removal system that significantly affect percolation. Increasing the leachate collection or lateral drainage rate reduces percolation by lowering the leachate depth or head controlling the percolation rate and reducing the quantity of leachate available for percolation. In practical terms, slopes greater than 5 percent and drain spacings less than 50 feet are not desirable. Therefore, only selection of drainage media having very high hydraulic conductivity can significantly increase the drainage rate and lower the leachate depth without adverse practical consequences. Sands having hydraulic conductivity greater than 2×10^{-2} cm/sec are commonly available as are gravels and plastic drainage nets. Sands used as drainage media in the laboratory and field studies had hydraulic conductivities that were much greater than the recommended value of 1×10^{-2} cm/sec. Consequently, higher hydraulic conductivities should be recommended.

Final Cover

Final covers affect percolation through the base of the landfill by controlling the infiltration of water into the waste. The cover is composed of a vegetated top cover and a liner and lateral drainage system that is comparable to the bottom liner and primary leachate collection and removal system discussed above. The evaluation and recommendations presented above for those systems also apply to the final cover. The remaining component of the final cover to be evaluated for its effect on percolation is the vegetated top cover.

The HELP model simulations indicate that the vegetated top cover has very little effect on percolation through the final cover. Decreases in runoff or increases in infiltration are offset by increases in evapotranspiration and lateral drainage, yielding only small effects on percolation.

Summary

Saturated hydraulic conductivity is the most important design parameter for minimizing percolation. Care should be taken to recommend the highest hydraulic conductivity that is commonly available for drainage media. Similarly, the lowest saturated hydraulic conductivity practically obtainable should be selected as guidance for soil liners. Changes in other design parameters yield much smaller effects on percolation if kept within a prudent range. The bottom liner should include a FML to minimize potential migration from the facility in the event that the top liner leaks. A composite bottom liner also ensures that leakage from the top liner will be detected.

SECTION 6

SIMULATION OF UNIVERSITY OF WISCONSIN-MADISON LYSIMETER CELLS

From 1970 to 1977, eight large lysimeter cells filled with either shredded or unprocessed refuse were monitored for surface runoff and leachate production at the University of Wisconsin-Madison (13). The general purpose of the study was to determine the effect on landfill performance of shredding the refuse prior to placement and covering the refuse with a soil layer. The HELP model was used to simulate the performance of these cells using climatological data recorded near the site. Comparisons are shown between model predictions and field measurements.

SITE DESCRIPTION

The test site was located in Madison, WI, where the average temperature is 45°F and the average annual precipitation is 31 inches. The minimum daily temperature falls below freezing on 163 days per year. The average daily solar radiation is approximately 330 langleys.

Each cell was 60 feet long by 30 feet wide and had depths of 4 to 8 feet. Cells were underlain with a 4-inch layer of crushed granite over a 6-mil polyethylene barrier. Bottom slopes of approximately 3 percent directed leachate to a collection box at the center of the cell. The collection box was periodically pumped, and the leachate volume was measured. The top surface of each cell was sloped at 3 percent toward one of the 60-foot walls. A collection trough along this wall directed runoff to a tank outside the cell where volume measurements were made. The depth of refuse, presence of soil cover, and condition of refuse (shredded or unprocessed) varied within each cell. Cell characteristics and dimensions are summarized in Table 8 and Figure 18.

SELECTION OF MODEL INPUT VALUES

The HELP simulations in this analysis used daily precipitation and mean monthly temperature values taken from the National Oceanic and Atmospheric Administration (NOAA) weather station at Madison, WI. Solar radiation values used were the default values for Madison incorporated in the HELP model. Other parameters were assigned values based on descriptions of the lysimeters and are summarized in Table 9 (13). As indicated in this table, covered and uncovered cells were modeled separately. However, no attempt was made to differentiate between shredded and unprocessed waste.

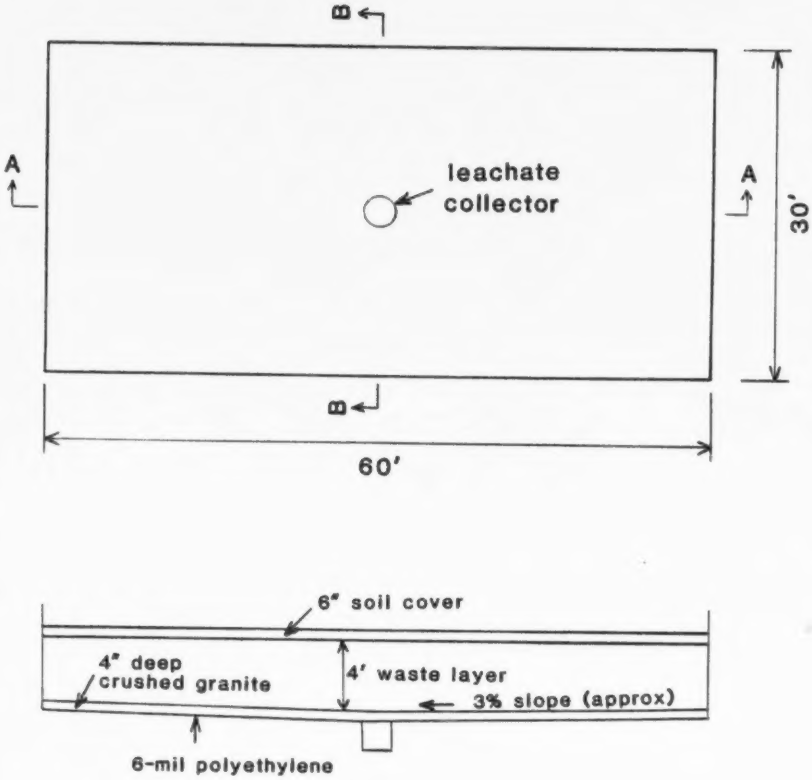
TABLE 8. UNIVERSITY OF WISCONSIN-MADISON CELL CHARACTERISTICS

Cell	Depth (ft)	Cover	Refuse Type	Period of Test
Cell 1	4	6-in. Soil Layer	Unprocessed	Sep 1970-May 1976
Cell 2	4	6-in. Soil Layer*	Shredded	Sep 1970-May 1976
Cell 3	4**	6-in. Soil Layer	Shredded	Sep 1970-June 1977
Cell 4	4**	No Cover	Shredded	Sep 1970-June 1977
Cell 5	4	No Cover	Unprocessed	Aug 1972-June 1977
Cell 6	4	No Cover	Shredded & Unprocessed†	Aug 1972-June 1977
Cell 7	8	No Cover	Shredded	Aug 1972-June 1977
Cell 8	8	6-in. Soil Layer	Unprocessed	Aug 1972-June 1977

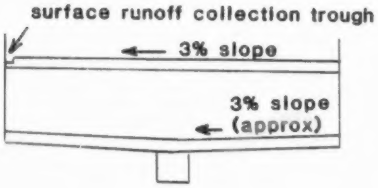
* Covered 6 months after initial placement. Covered again in July 1975 immediately following the placement of an additional 4 feet of refuse.

** Depth increased to 8 ft. in July 1975.

† 66 tons of unprocessed refuse covered with 30 tons of shredded refuse.


B
A
leachate collector
A
30'
B
60'
6" soil cover
4" deep crushed granite
4' waste layer
3% slope (approx)
6-mil polyethylene

SECTION A-A


surface runoff collection trough
3% slope
3% slope (approx)

SECTION B-B

Figure 18. Cell dimensions for University of Wisconsin-Madison cells.

TABLE 9. INPUT DATA FOR SIMULATION OF UNIVERSITY OF WISCONSIN-MADISON CELLS*

Parameter	Covered Cell	Uncovered Cells
No. of layers	4	4
Layer 1		
Thickness (in.)	6	6
Layer type	1	1
Soil texture	9	19
Is layer compacted?	Yes	Partial compaction**
Layer 2		
Thickness (in.)	48 or 96	42 or 90
Layer type	4	4
Soil texture	19	19
Layer 3		
Thickness (in.)	4	4
Layer type	2	2
Soil texture	1	1
Is layer compacted?	No	No
Layer 4		
Thickness (in.)	1	1
Layer type	5	5
Soil texture	21	21
Liner leakage fraction	0	0
Type of vegetation	Poor	Fair
SCS runoff curve no.	84.4	79
Evaporative depth (in.)	8	12
Surface area (sq ft)	1800	1800
Slope of lateral drainage (%)	3	3
Drainage length (ft)	25	25

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* Input data terminology defined in the HELP model documentation (1) and user's guide (2).

** Partial compaction was assumed for the uncovered cells due to effects of weathering at the surface. This was simulated by using a hydraulic conductivity equal to the default value for soil texture 19 divided by 5.0. Then, this resulting hydraulic conductivity underwent the normal adjustment for type of vegetation.

Since hydraulic parameters for the soil and waste were not available, default characteristics were used. Soil texture 9 was chosen for the soil cover, described as sandy silt. Soil texture 19 was chosen to describe the waste.

The vegetation on the surface of the cells was described to be mixed volunteer vegetation, comparable to meadow grass, which became established on both covered and uncovered cells over a several-year period (13). This vegetation grew more quickly and more densely on the uncovered cells; therefore, "fair grass" was chosen to describe the vegetation on the uncovered cells and "poor grass" was chosen for the covered cells. Corresponding evaporative depths were set at 12 and 8 inches, respectively, to be consistent with (yet somewhat less conservative than) the suggested values in the HELP model. Default leaf area index values and winter cover factors presented in the HELP model User's Guide were adopted for these two types of vegetation (2).

SCS runoff curve numbers were selected by using observed precipitation and runoff data for several storms to estimate separate curve numbers for the covered and uncovered cells. Since only monthly runoff data were available, this method was expected to produce only approximate values. The results were generally consistent with the minimum infiltration rate method presented in the HELP model user's guide (2). Calibration was required since curve numbers are not available in the literature for municipal waste. Calibration in this manner reduces the validity of the verification of the runoff component, but only a small portion of the data was used for calibration. Also, the calibration procedure did not use the HELP model or the SCS curve number procedure as applied in the HELP model. Therefore, the value of this verification study should not be significantly diminished by this calibration.

The soil cover of the covered cells was assumed to be compacted based on a description of cell construction activities. The top layer of the uncovered cells was assumed to be partially compacted due to weathering at the surface, thus influencing the hydraulic conductivity as outlined in Table 9.

RESULTS OF MODEL SIMULATIONS

The simulation period for the two HELP runs began with January 1970, whereas the period of field monitoring began in September 1970 for Cells 1 through 4 and August 1972 for Cells 5 through 8. This simulation period did not exactly match the period of field monitoring since HELP must start at the beginning of a calendar year. Also, this initial simulation period and the first 2 years of field monitoring were treated as periods of equilibration for both the HELP model and the test cells and therefore are not plotted in the accompanying figures. It was assumed that this period of equilibration was necessary to bring internal moisture to normal levels and to establish a weathered surface on the uncovered cells and volunteer vegetation on all the cells.

The simulation results are presented in the form of cumulative and monthly comparisons between model predictions and field measurements for the following components of the water balance: (a) runoff, (b) evapotranspiration plus change in landfill moisture storage (ET+DS), and (c) leachate drainage. Field "measurements" of ET+DS were actually computed values based on the following relationship:

$$ET+DS = PRCP - RNF - DRG \quad (28)$$

where PRCP = measured precipitation, RNF = measured runoff, and DRG = measured leachate drainage. It was assumed that all leachate was recovered by lateral drainage due to the presence of an impervious synthetic liner below the lateral drainage layer.

Comparisons of accumulated runoff, ET+DS, and leachate drainage for each individual cell are plotted in Figures 19 through 26. The same curves (for the period of overlapping records) are plotted together in Figure 27 for covered cells and in Figure 28 for uncovered cells. Monthly comparisons of runoff, ET+DS, and leachate drainage for each individual cell are plotted in Figures 29 through 36. Tables 10 and 11 summarize the differences between measured and predicted results.

For the covered cells, the simulations overpredicted cumulative runoff for two cells and underpredicted cumulative runoff for the remaining two cells. The runoff simulations generally compare well prior to a large storm in July 1975. As seen in Table 10, measured runoff accounted for an average of 7.6 percent of the precipitation from the covered cells. The standard deviation, s, of the measured runoff fraction was 2.2 percent. The HELP model predicted 8.1 percent, yielding an error of 0.5 percent (s = 2.6 percent) of the precipitation or a relative error of 6.8 percent of the measured runoff. The measured ET+DS was 68.9 percent (s = 3.1 percent) of the precipitation, while the predicted value was 67.1 percent. The model underpredicted by 1.8 percent (s = 3.3 percent) of the precipitation or 2.6 percent of the measured ET+DS. Measured leachate drainage accounted for 23.5 percent (s = 4.6 percent) of the precipitation while the model estimated 24.8 percent. The average error was 1.4 percent (s = 3.7 percent) of the precipitation, and the relative error was 6.0 percent of the measured leachate. In all cases the mean error in the HELP model predictions was significantly less than the standard deviation of the measured values.

Simulation of the uncovered cells was not as successful, particularly for leachate drainage. As seen in Table 11, measured runoff accounted for 3.4 percent (s = 0.5 percent) of the precipitation, while the HELP model estimated 2.7 percent. The model underestimated by 0.8 percent (s = 0.5 percent) of the precipitation, yielding a relative error of -23.5 percent of the measured runoff. The measured ET+DS was 83.9 percent (s = 9.1 percent) of the precipitation, while the predicted value was 78.0 percent. The model underpredicted by 5.9 percent (s = 10.1 percent) of the precipitation or 7.0 percent of the measured ET+DS. Leachate drainage accounted for 12.7 percent (s = 9.4 percent) of the precipitation. This large standard deviation shows the highly variable nature of uncovered waste. The model predicted 19.4 percent, producing an error of 6.7 percent (s = 10.2 percent) of the precipitation and a relative error of 52.8 percent of the measured leachate. For both covered and uncovered cells, the difference between predicted values and

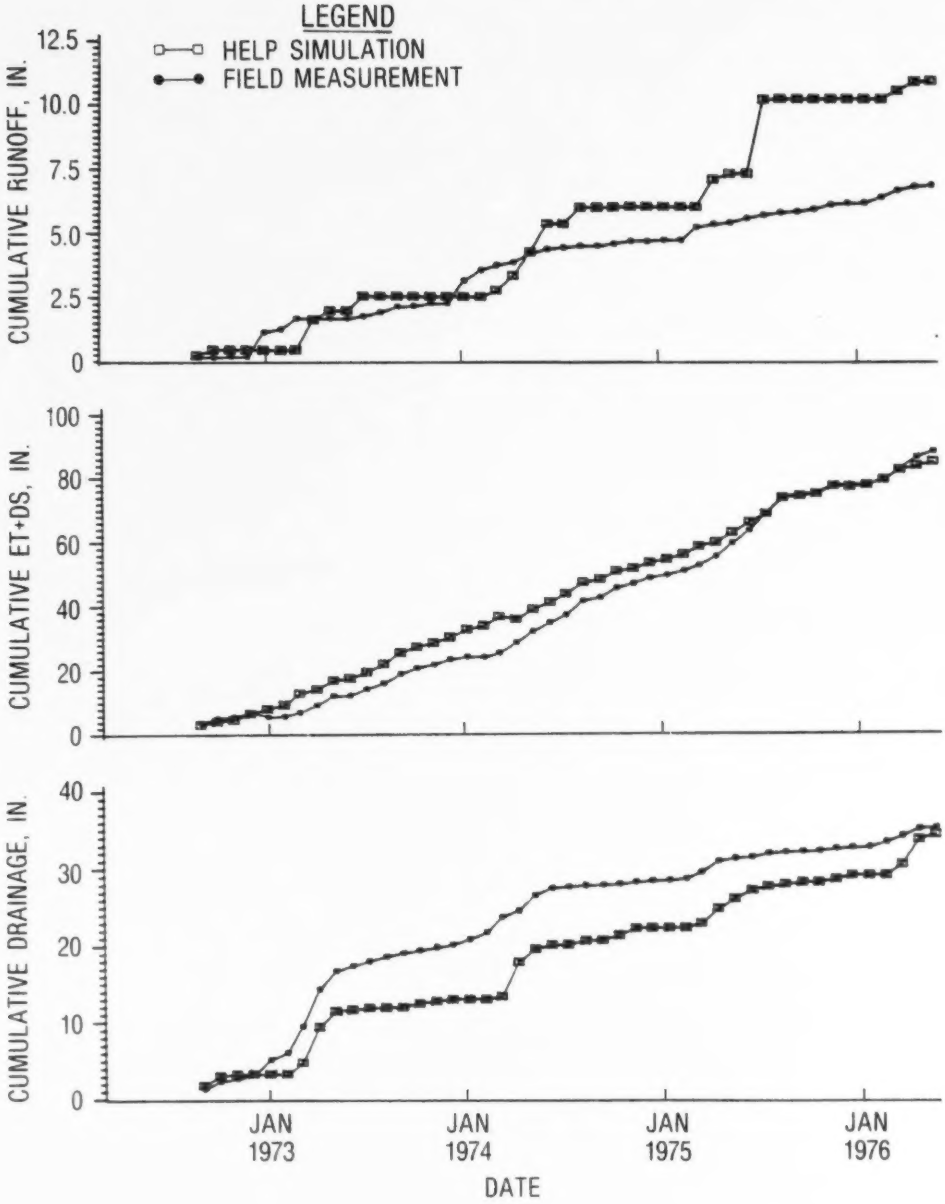


Figure 19. Field measurements for Cell 1 compared to HELP simulation for covered cells; cumulative comparisons.

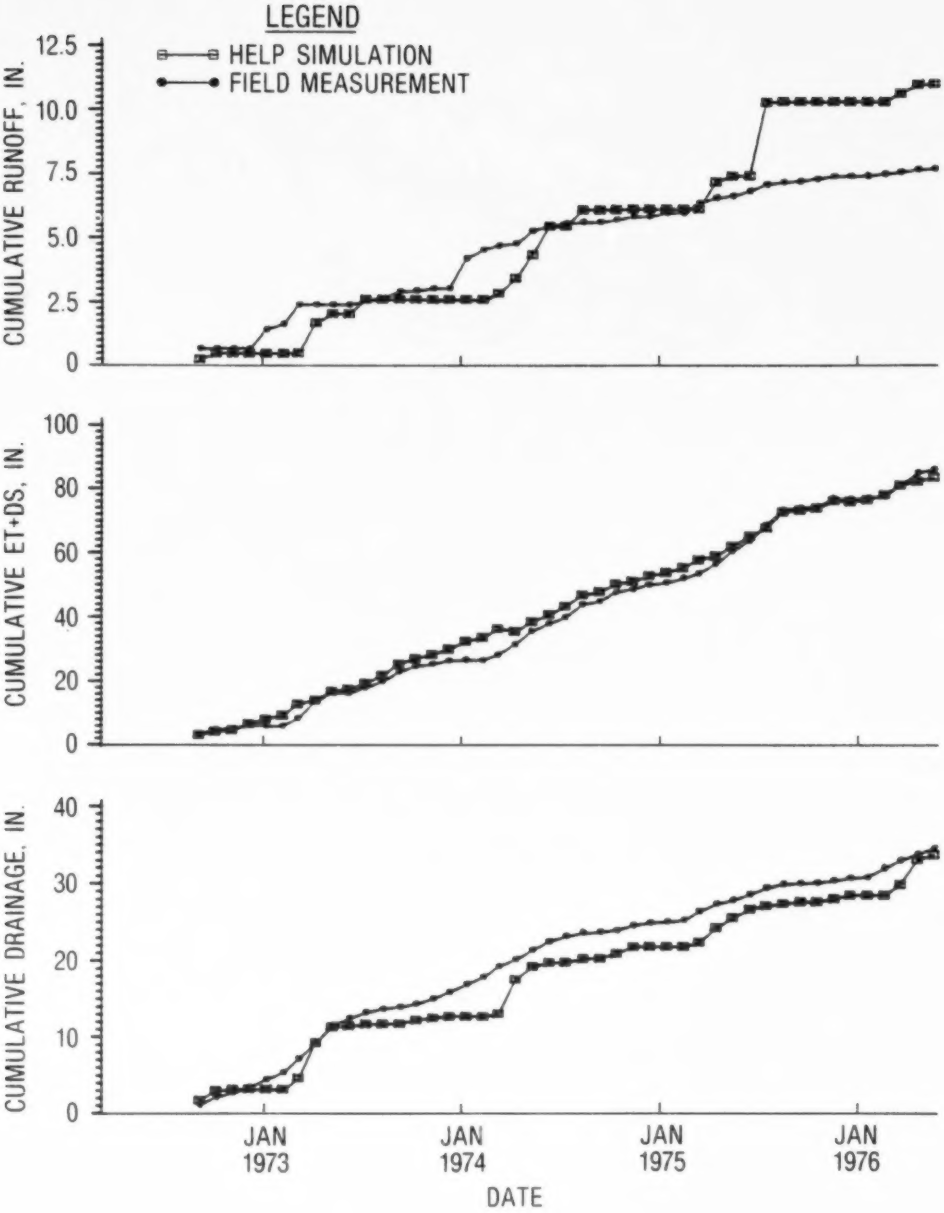


Figure 20. Field measurements for Cell 2 compared to HELP simulations for covered cells; cumulative comparisons.

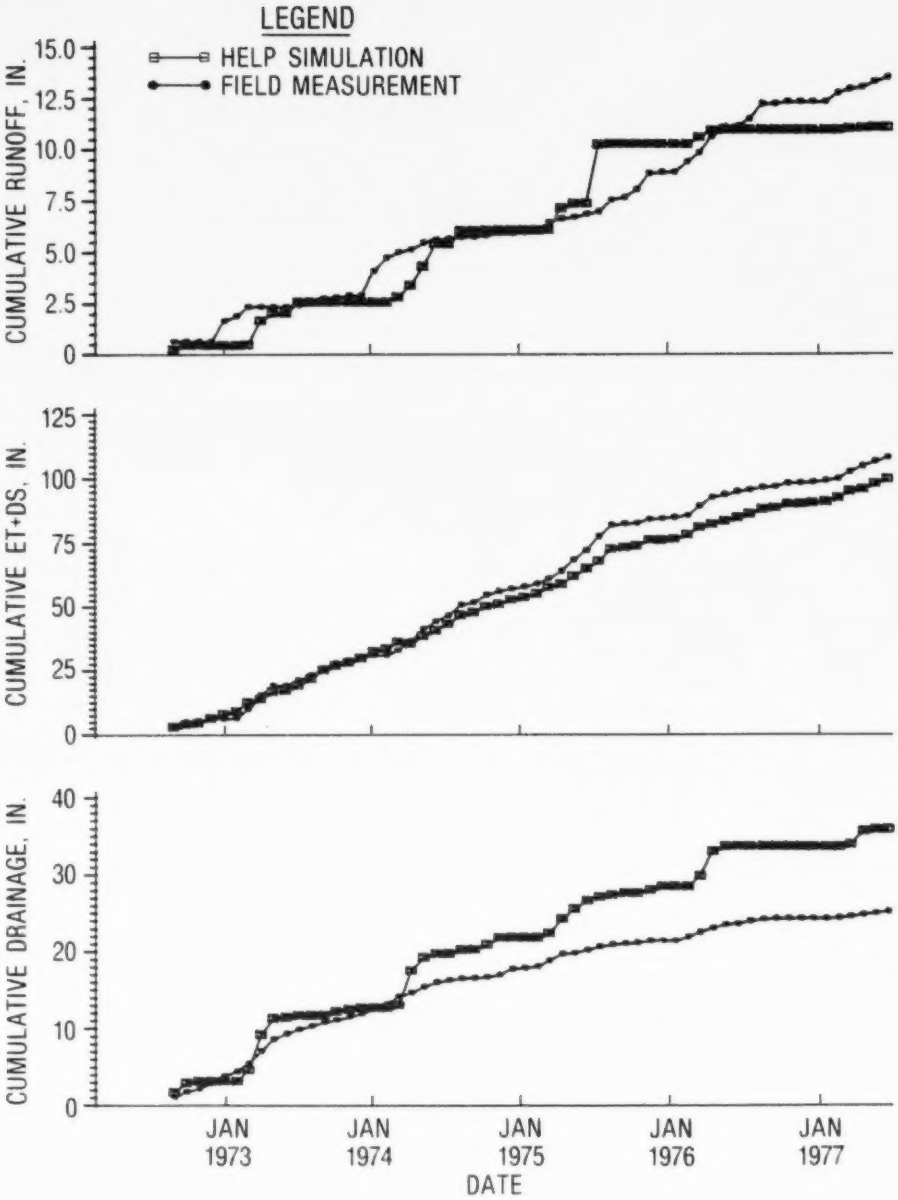


Figure 21. Field measurements for Cell 3 compared to HELP simulations for covered cells; cumulative comparisons.

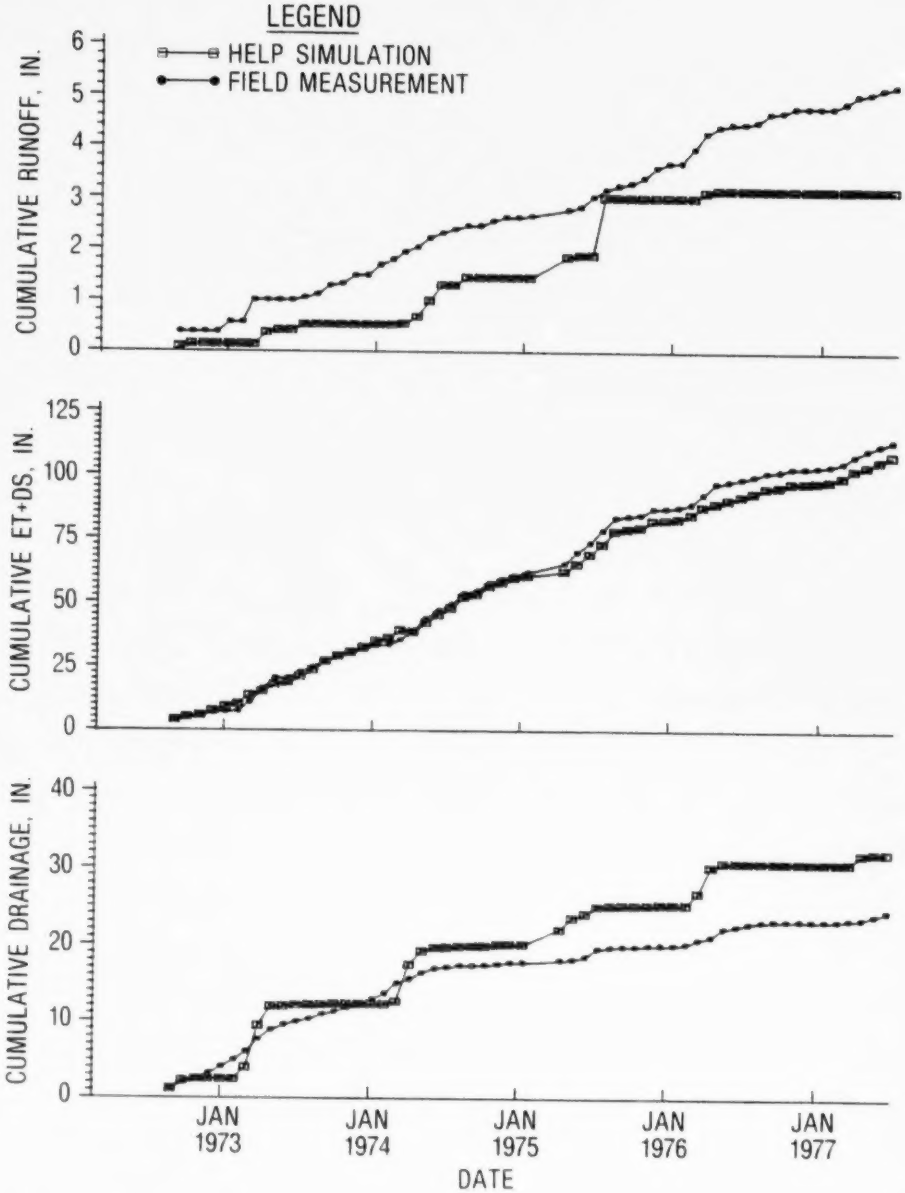


Figure 22. Field measurements for Cell 4 compared to HELP simulation for uncovered cells; cumulative comparisons.

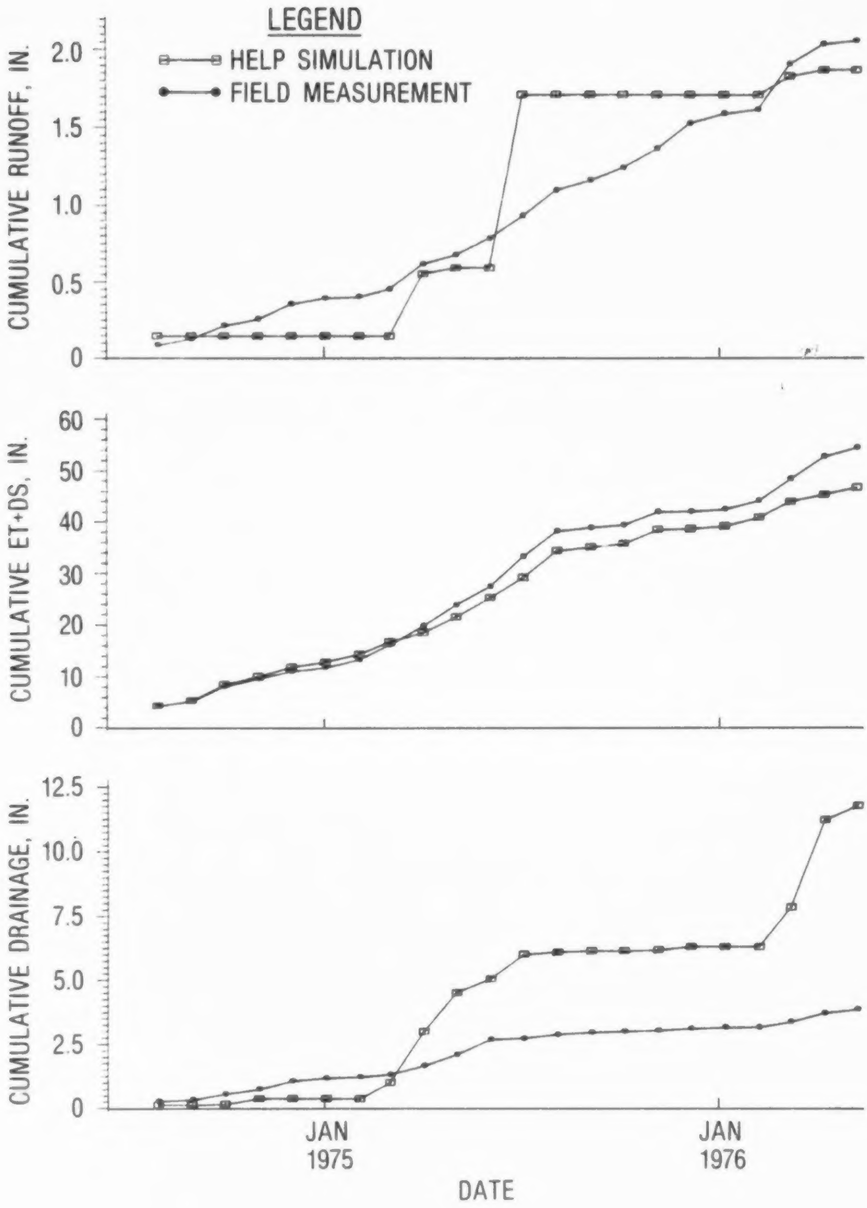


Figure 23. Field measurements for Cell 5 compared to HELP simulation for uncovered cells; cumulative comparisons.

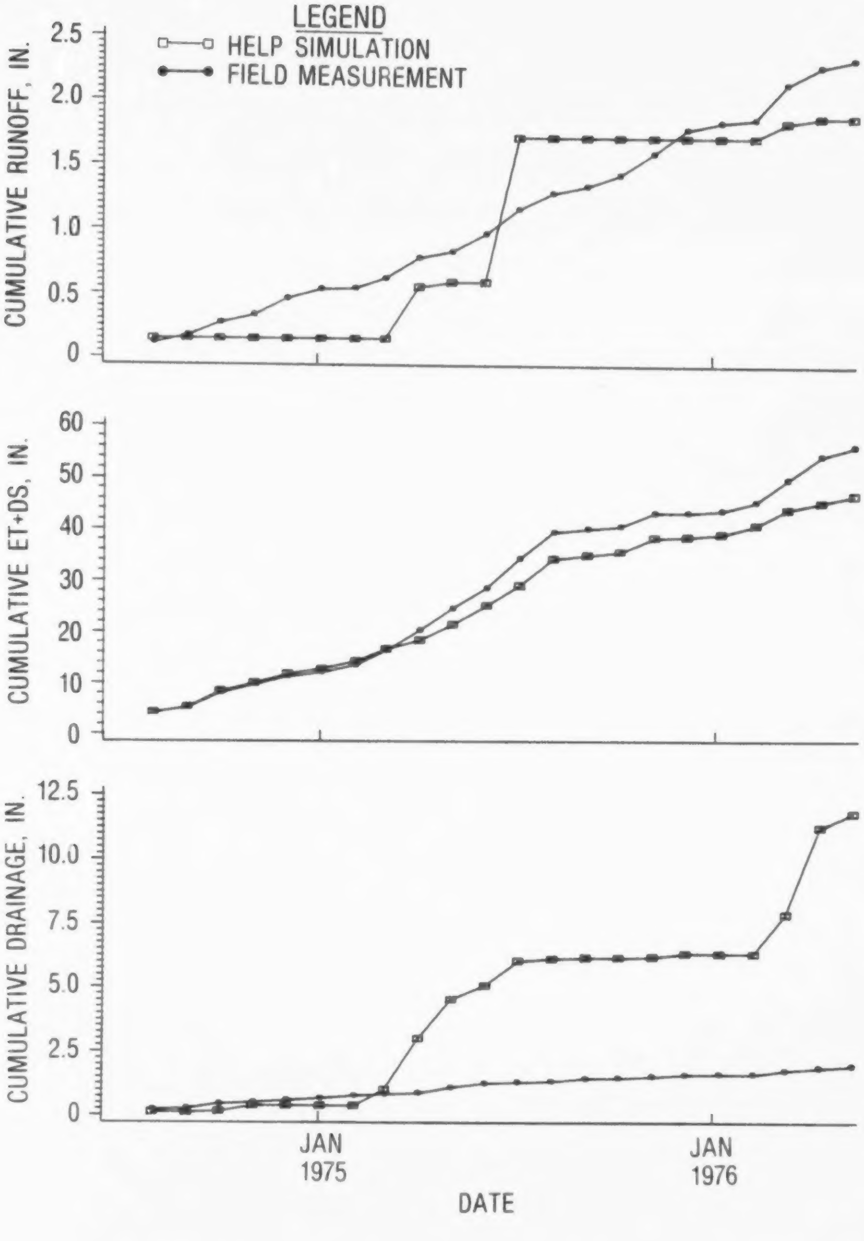


Figure 24. Field measurements for Cell 6 compared to HELP simulations for uncovered cells; cumulative comparisons.

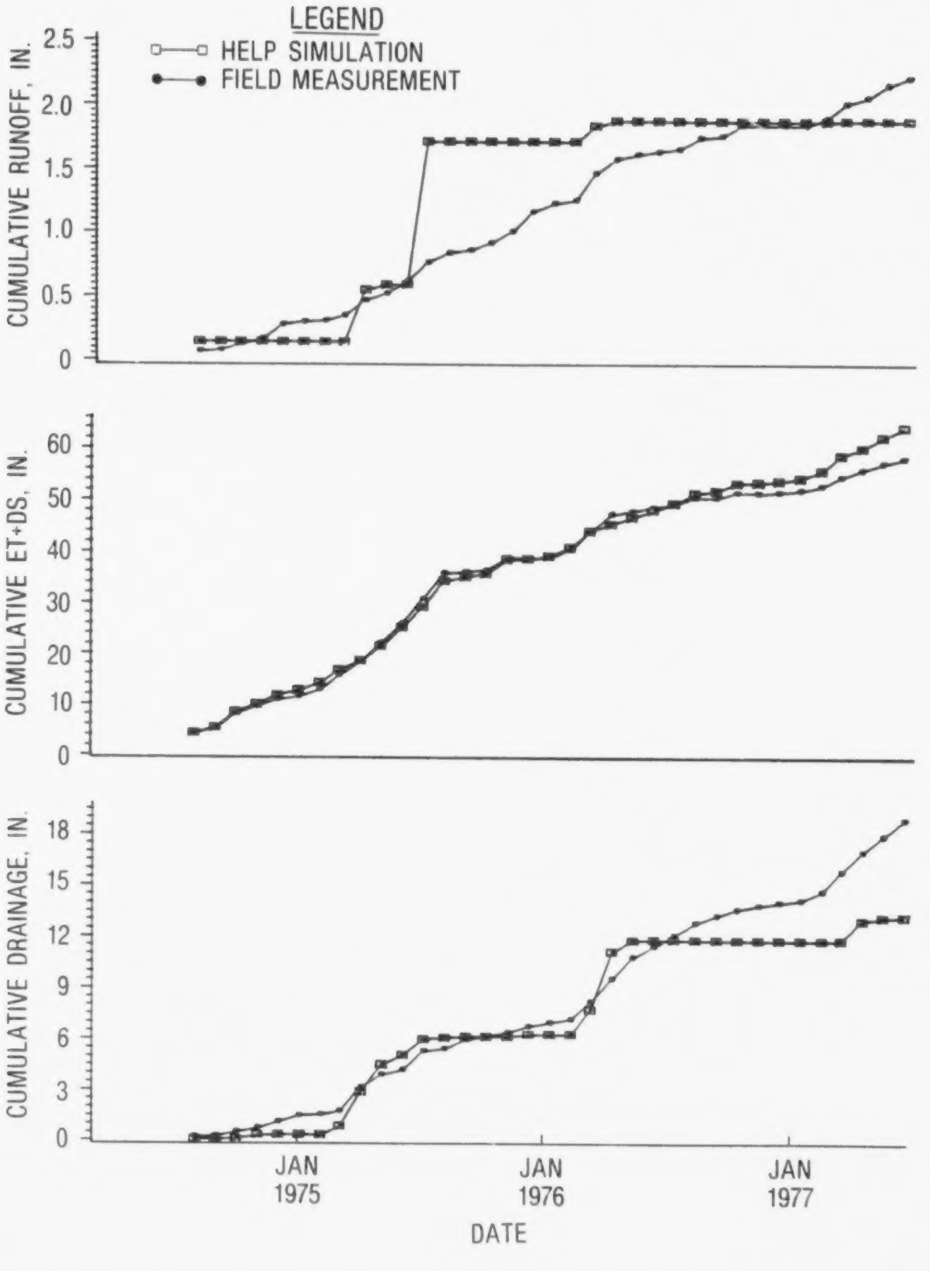


Figure 25. Field measurements for Cell 7 compared to HELP simulation for uncovered cells; cumulative comparisons.

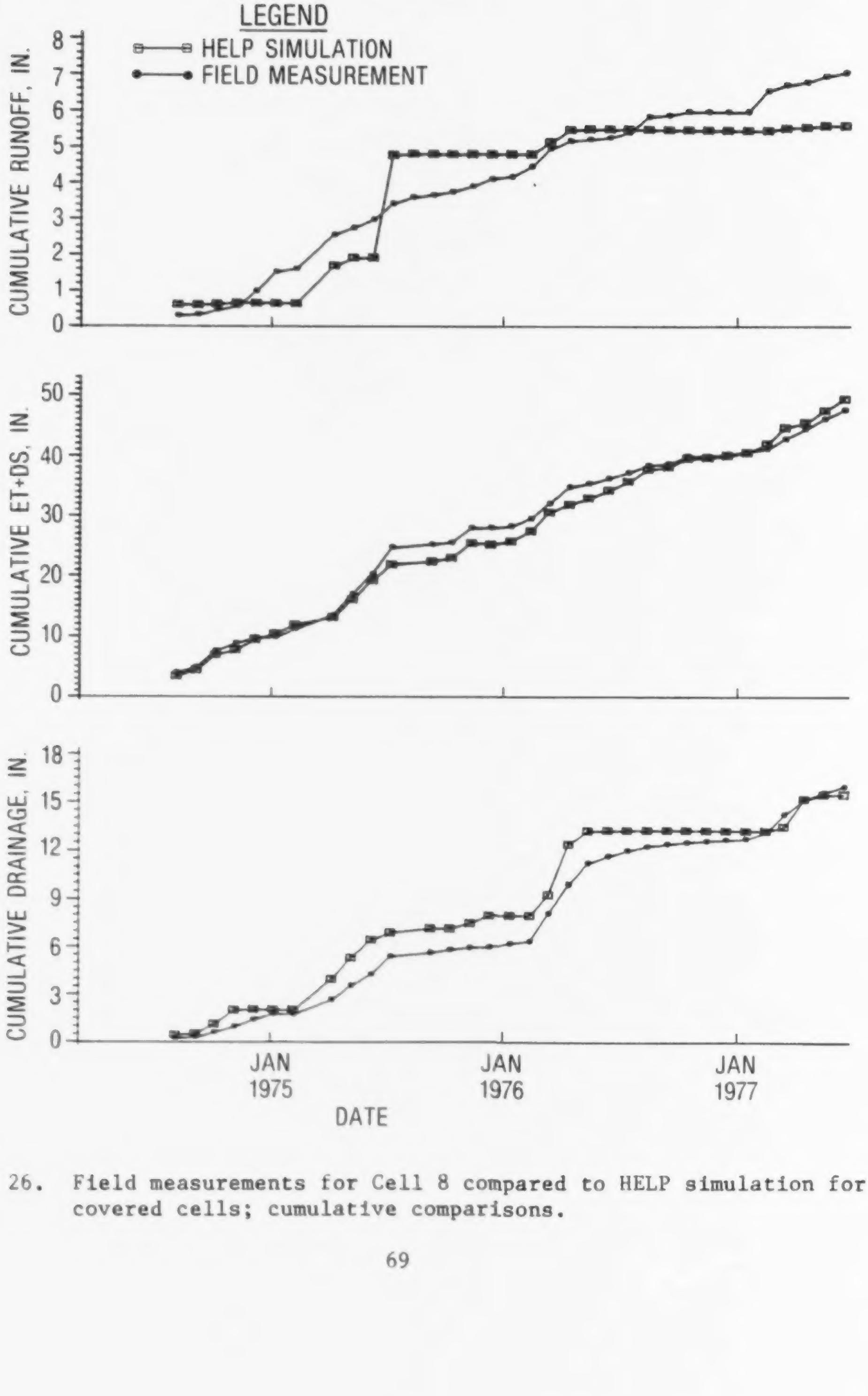


Figure 26. Field measurements for Cell 8 compared to HELP simulation for covered cells; cumulative comparisons.

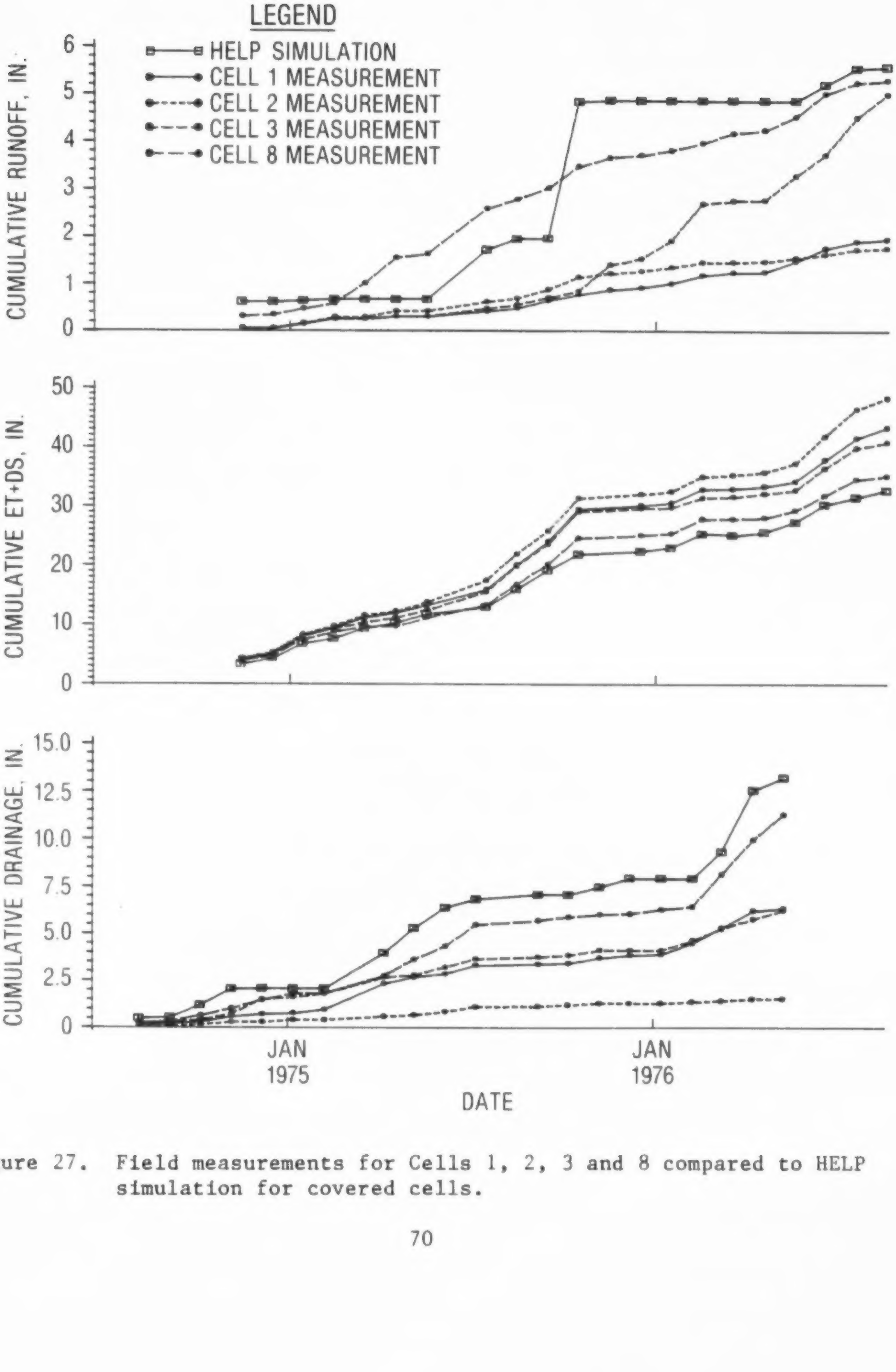


Figure 27. Field measurements for Cells 1, 2, 3 and 8 compared to HELP simulation for covered cells.

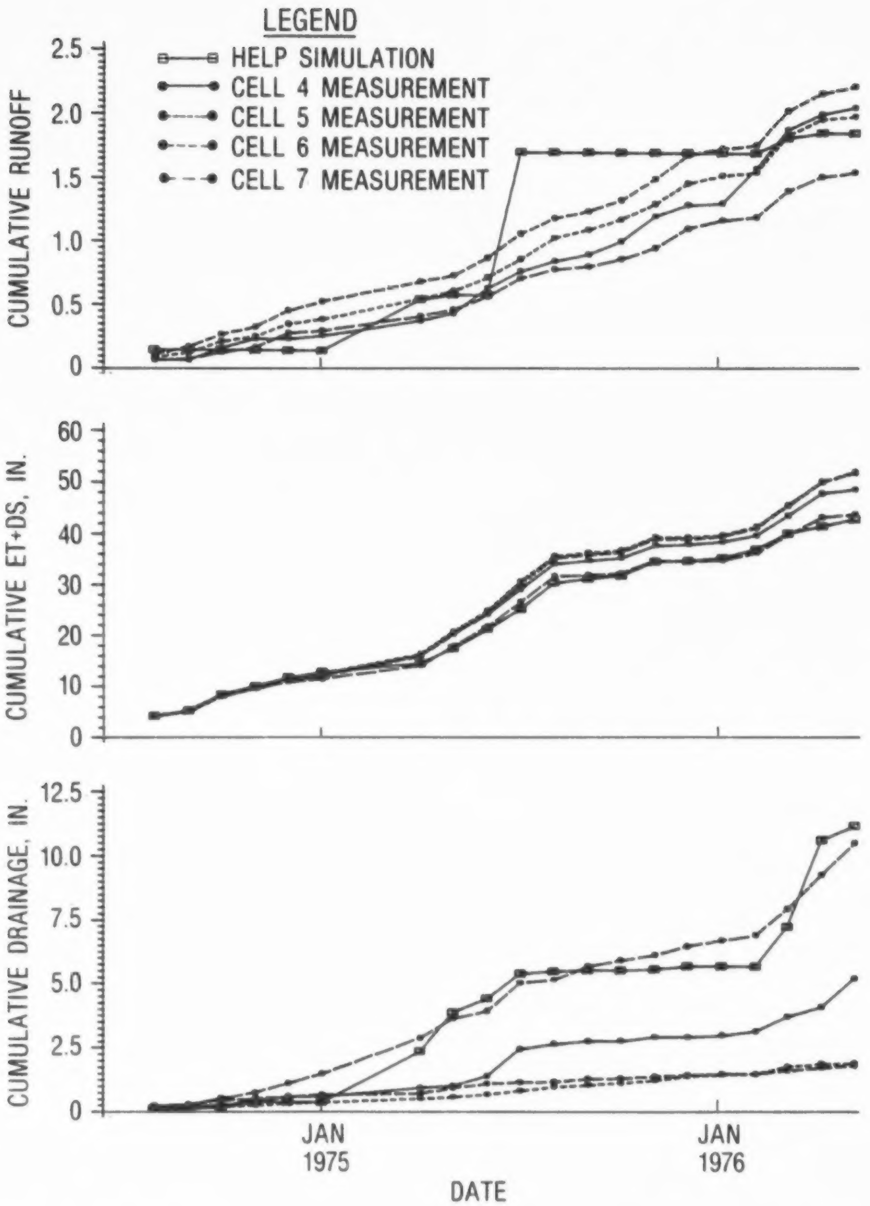


Figure 28. Field measurements for Cells 4, 5, 6 and 7 compared to HELP simulation for uncovered cells.

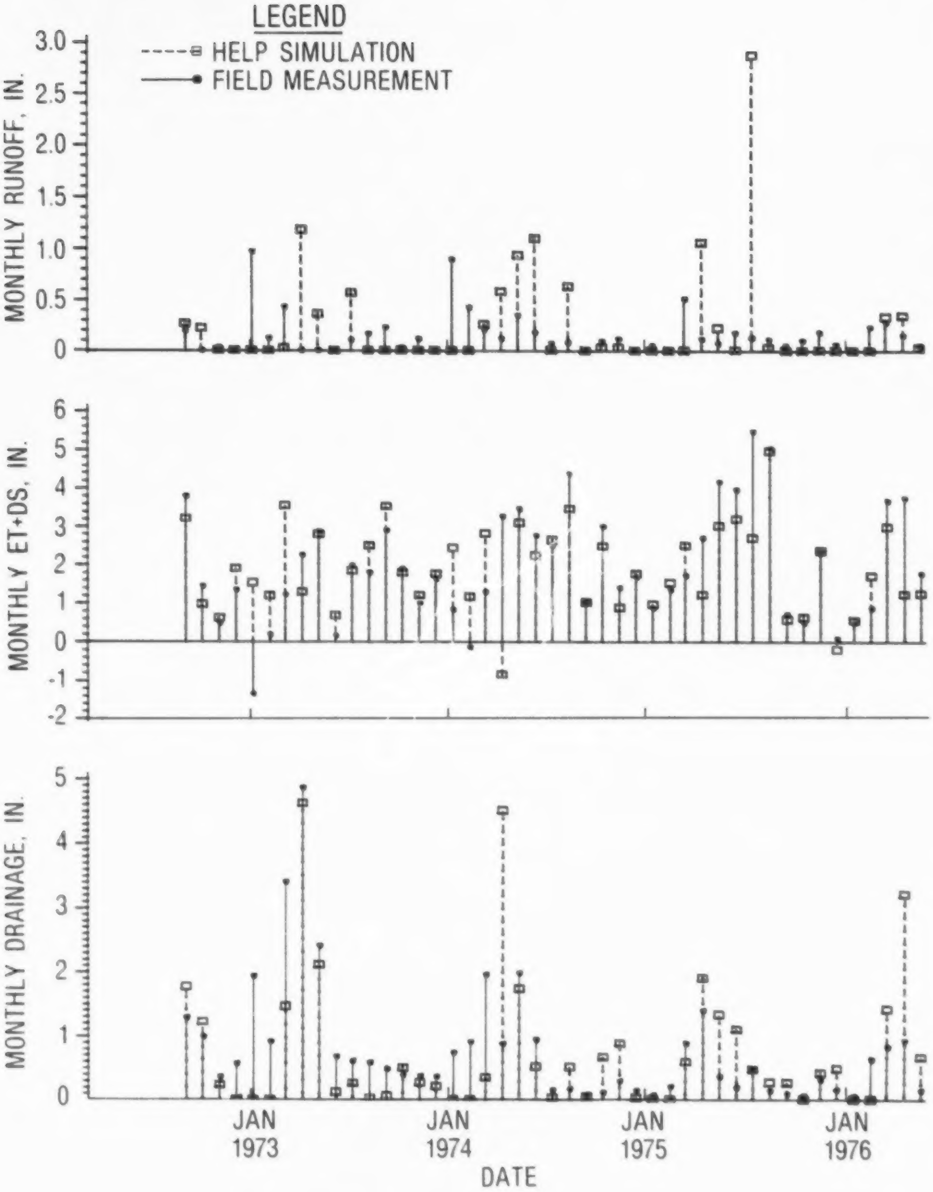


Figure 29. Field measurements for Cell 1 compared to HELP simulation for covered cells; monthly comparisons.

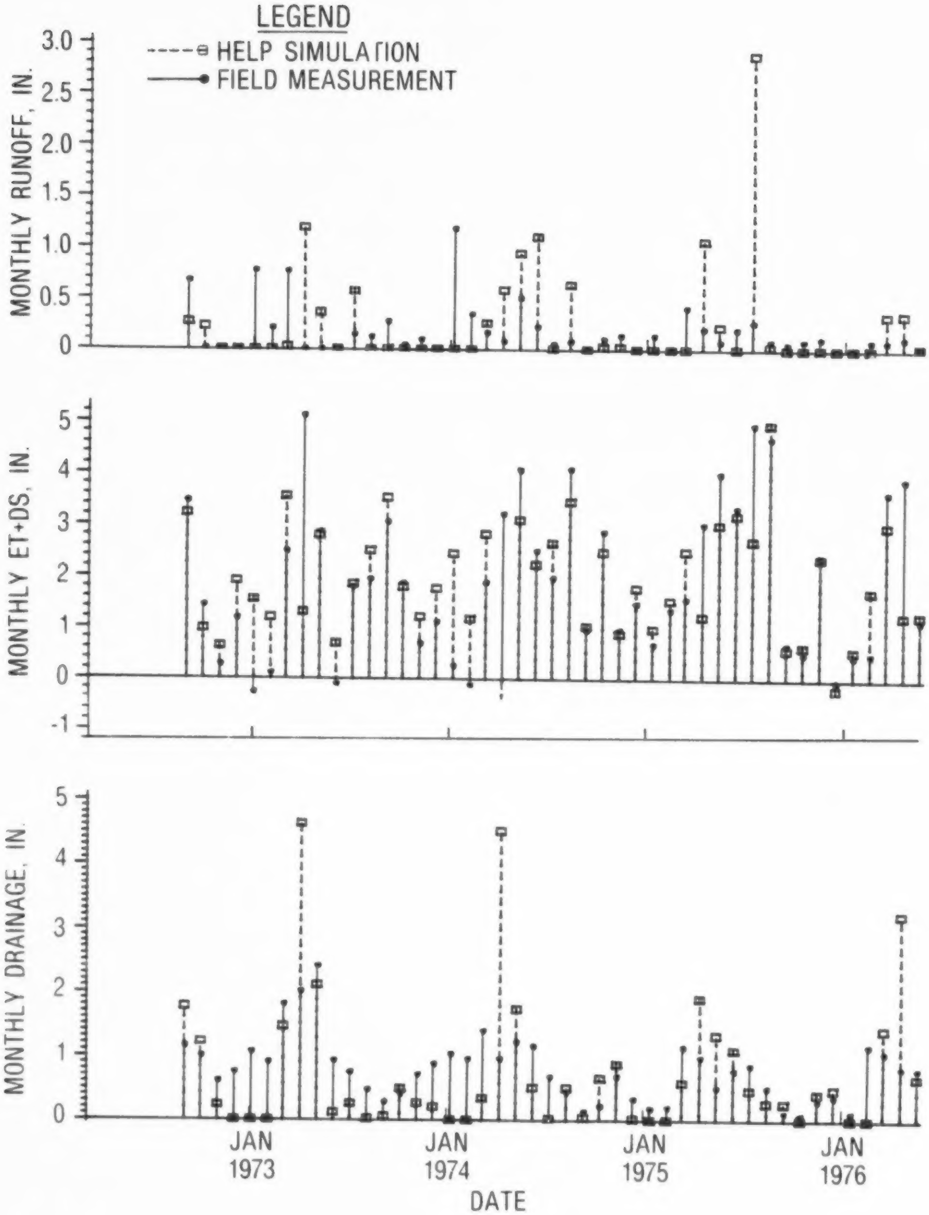


Figure 30. Field measurements for Cell 2 compared to HELP simulation for covered cells; monthly comparisons.

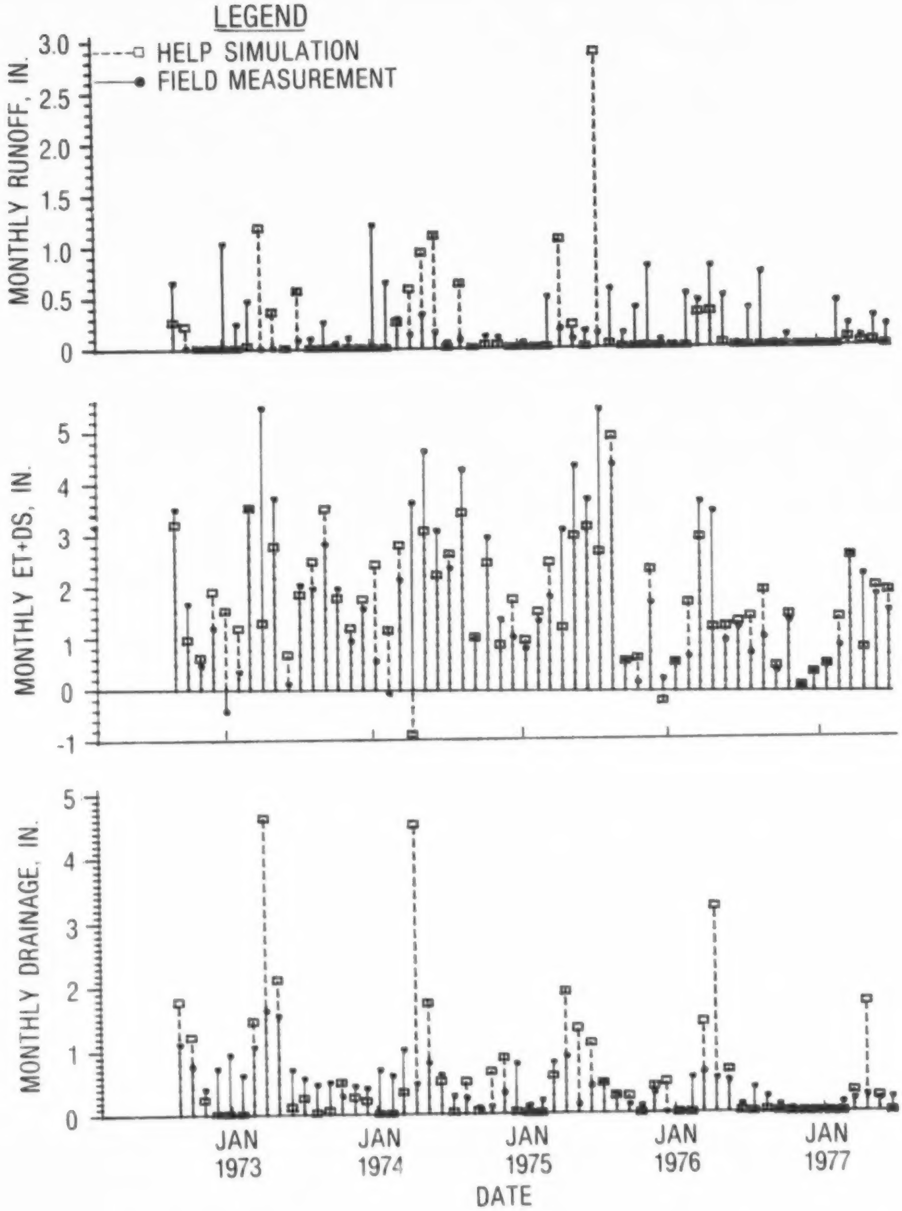


Figure 31. Field measurements for Cell 3 compared to HELP simulation for covered cells; monthly comparisons.

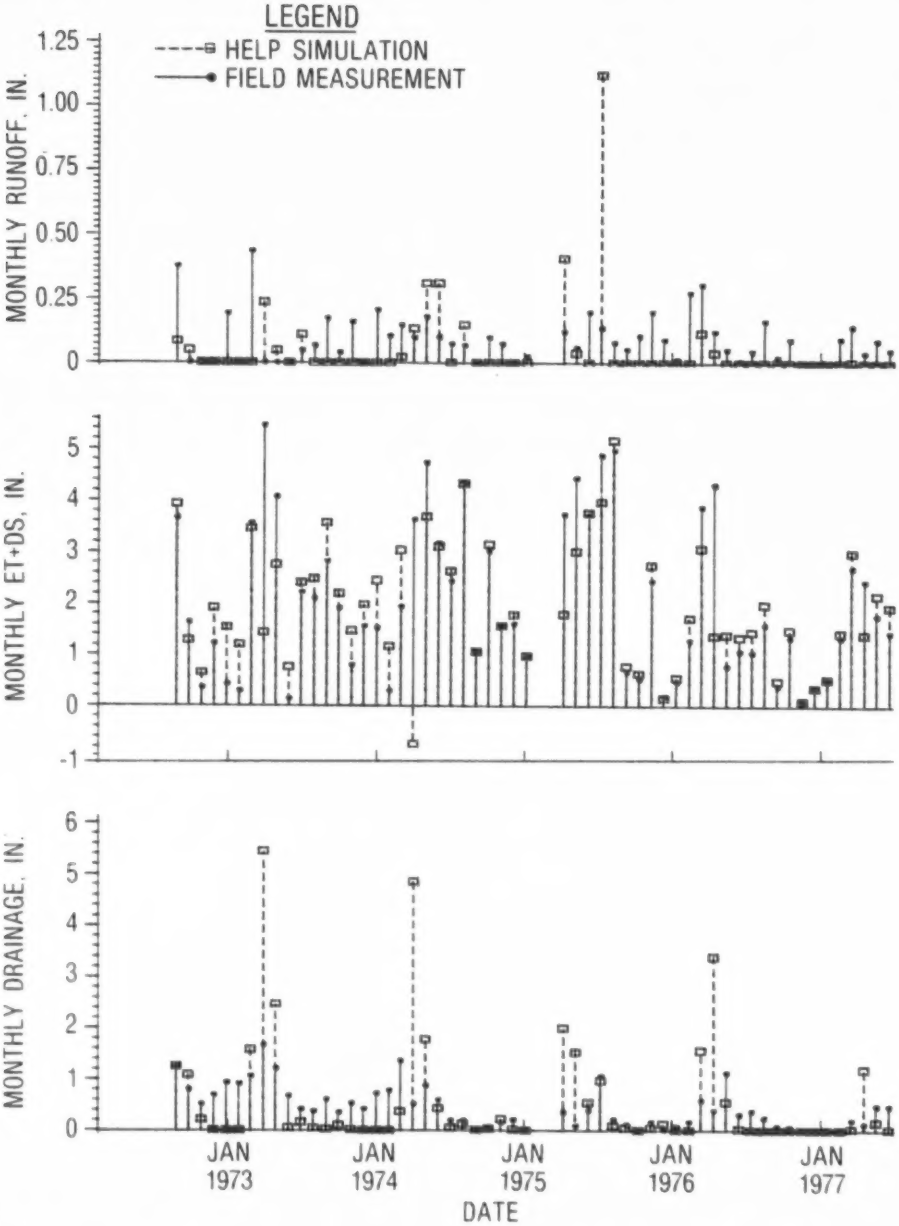


Figure 32. Field measurements for Cell 4 compared to HELP simulation for uncovered cells; monthly comparisons.

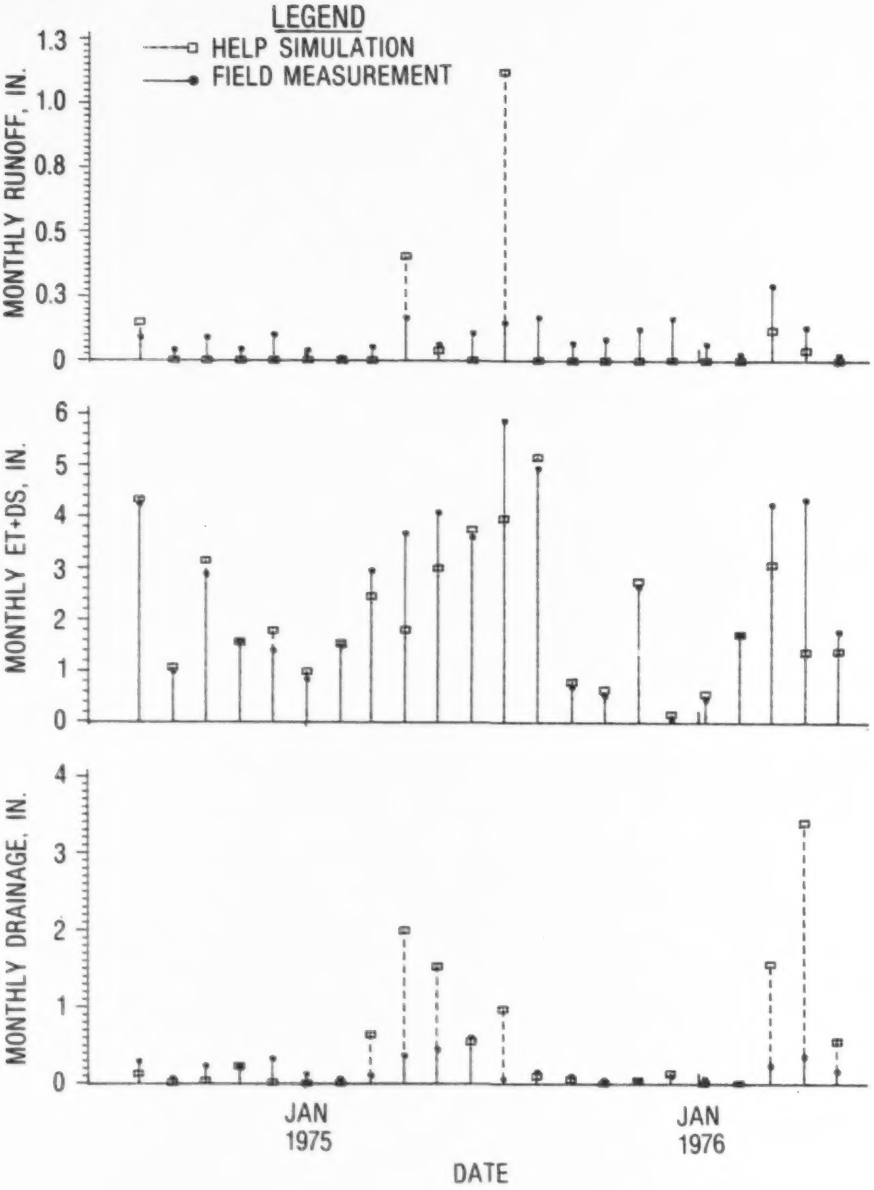


Figure 33. Field measurements for Cell 5 compared to HELP simulation for uncovered cells; monthly comparisons.

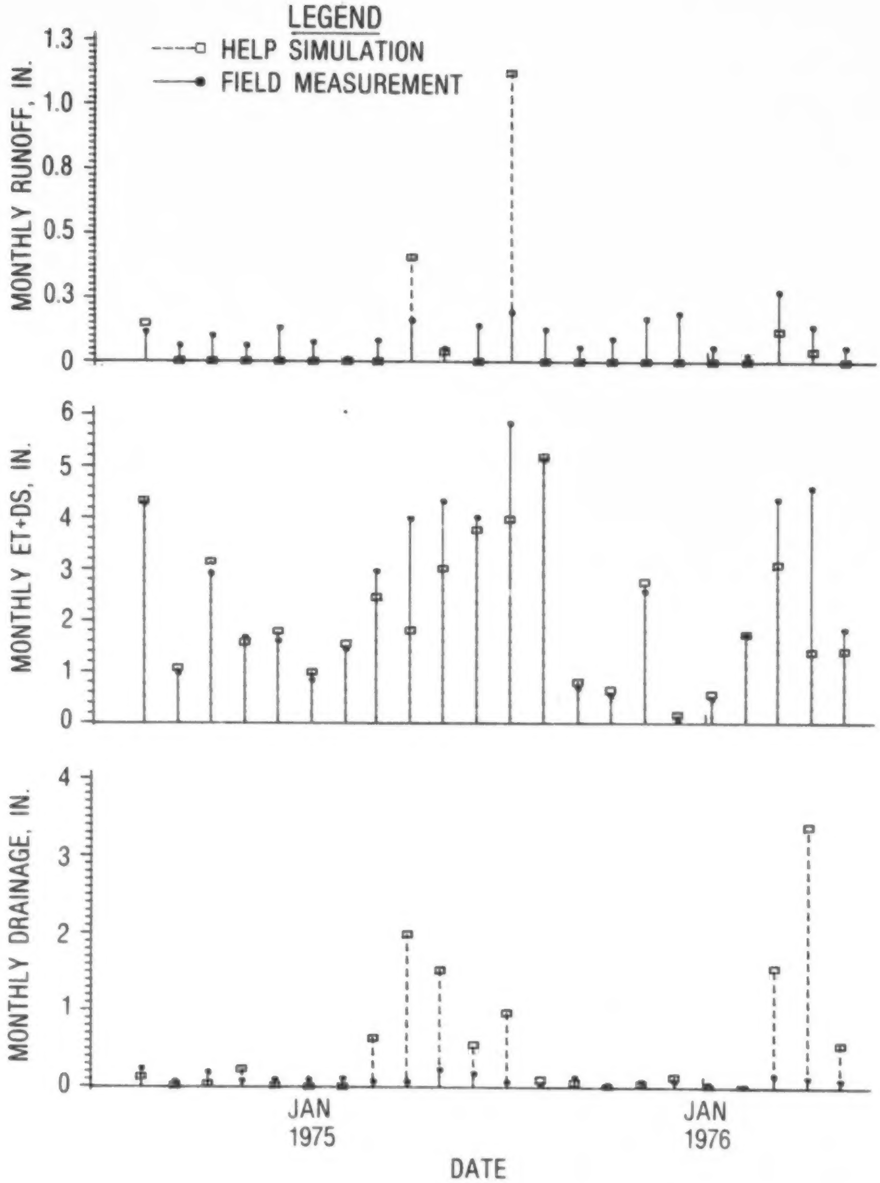


Figure 34. Field measurements for Cell 6 compared to HELP simulation for uncovered cells; monthly comparisons.

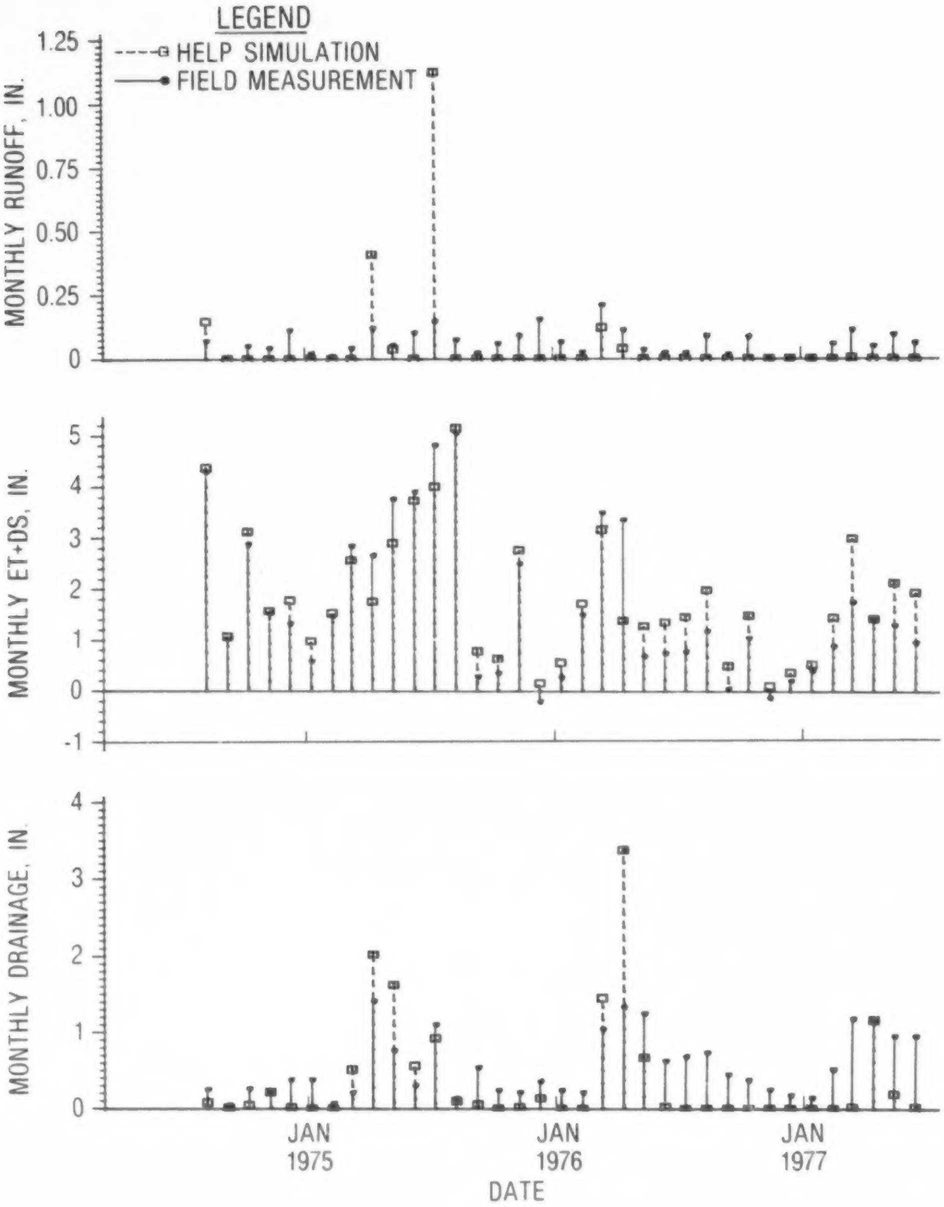


Figure 35. Field measurements for Cell 7 compared to HELP simulation for uncovered cells; monthly comparisons.

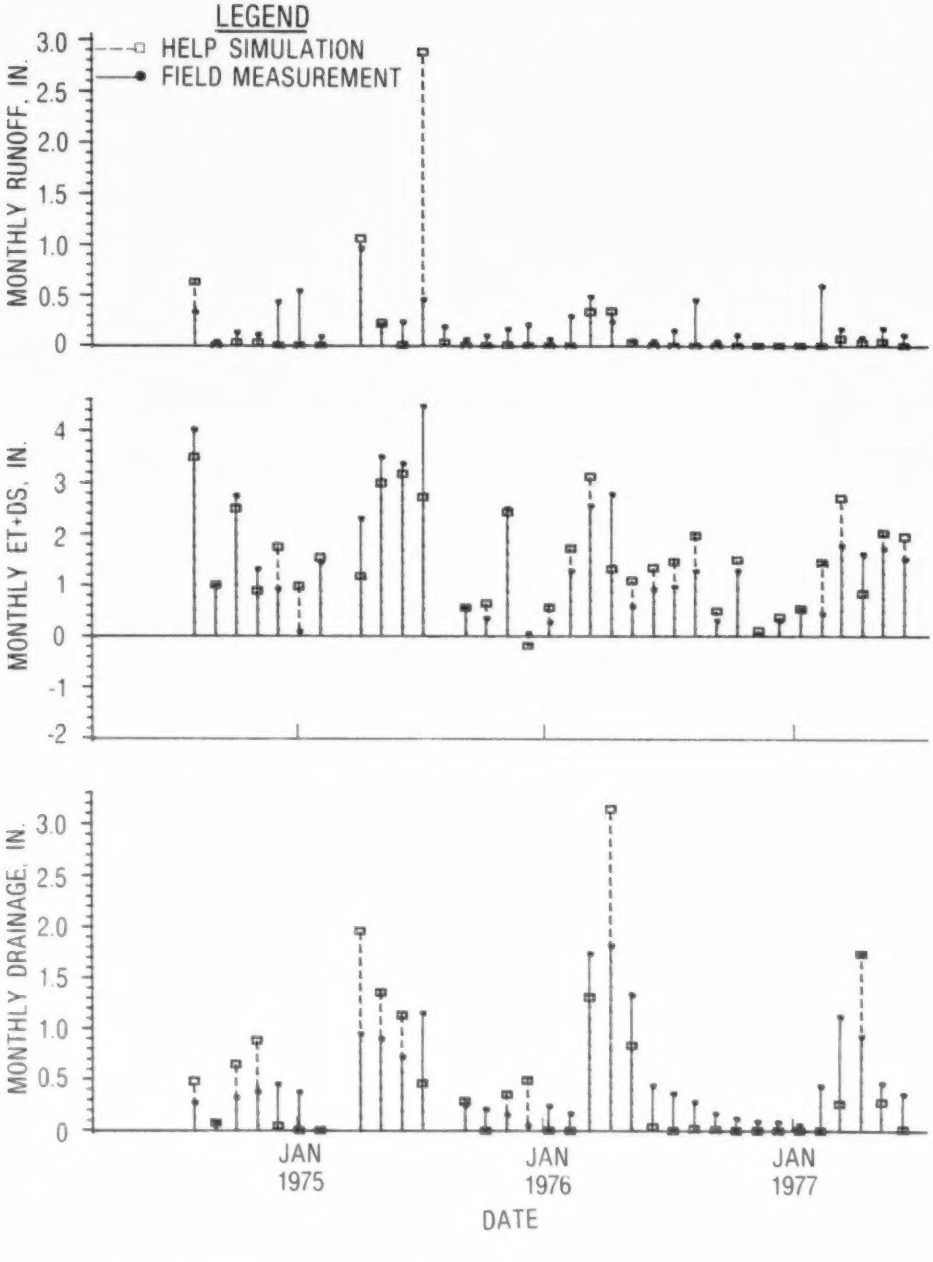


Figure 36. Field measurements for Cell 8 compared to HELP simulation for covered cells; monthly comparisons.

TABLE 10. DIFFERENCE BETWEEN CUMULATIVE HELP MODEL PREDICTIONS AND CUMULATIVE FIELD MEASUREMENTS FOR COVERED CELLS AT UNIVERSITY OF WISCONSIN-MADISON

	Runoff			
	Measured	Predicted	Error	
Cell No.	(% precip)	(% precip)	(% precip)	%
1	5.4	8.5	3.1	56
2	6.0	8.5	2.5	42
3	9.1	7.5	-1.6	-18
8	9.8	8.0	-1.8	-18
Mean	7.6	8.1	0.5	15
Std. Dev.	2.2	0.5	2.6	39

Mean Error as Percent
of Mean Measured Runoff = 6.8%

Range in Measured Runoff as Percent
of Mean Measured Runoff = 71% to 129%

	ET+DS			
	Measured	Predicted	Error	
Cell No.	(% precip)	(% precip)	(% precip)	%
1	67.7	65.3	-2.4	-3.5
2	67.1	65.3	-1.8	-2.7
3	73.6	68.0	-5.6	-7.6
8	67.4	69.9	2.5	3.7
Mean	68.9	67.1	-1.8	-2.5
Std. Dev.	3.1	2.2	3.3	4.7

Mean Error as Percent
of Mean Measured ET+DS = -2.6%

Range in Measured ET+DS as Percent
of Mean Measured ET+DS = 97% to 107%

	Drainage			
	Measured	Predicted	Error	
Cell No.	(% precip)	(% precip)	(% precip)	%
1	26.9	26.3	-0.6	-2.2
2	26.9	26.3	-0.6	-2.2
3	17.3	24.5	7.2	41.6
8	22.7	22.1	-0.6	-2.7
Mean	23.5	24.8	1.4	8.7
Std. Dev.	4.6	2.0	3.7	22.0

Mean Error as Percent
of Mean Measured Drainage = 6.0%

Range in Measured Drainage as Percent
of Mean Measured Drainage = 74% to 114%

TABLE 11. DIFFERENCE BETWEEN CUMULATIVE HELP MODEL PREDICTIONS AND CUMULATIVE FIELD MEASUREMENTS FOR UNCOVERED CELLS AT UNIVERSITY OF WISCONSIN-MADISON

	Runoff			
	Measured	Predicted	Error	
Cell No.	(% precip)	(% precip)	(% precip)	%
4	3.6	2.2	-1.4	-39
5	3.4	3.0	-0.4	-12
6	3.9	3.0	-0.9	-23
7	2.8	2.4	-0.4	-14
Mean	3.4	2.7	-0.8	-22
Std. Dev.	0.5	0.4	0.5	12

Mean Error as Percent
of Mean Measured Runoff = -23.5%

Range in Measured Runoff as Percent
of Mean Measured Runoff = 82% to 115%

	ET+DS			
	Measured	Predicted	Error	
Cell No.	(% precip)	(% precip)	(% precip)	%
4	79.2	75.3	-3.9	-5
5	90.1	77.8	-12.3	-14
6	92.7	77.8	-14.9	-16
7	73.5	81.0	7.5	10
Mean	83.9	78.0	-5.9	-6
Std. Dev	9.1	2.3	10.1	12

Mean Error as Percent
of Mean Measured ET+DS = -7.0%

Range in Measured ET+DS as Percent
of Mean Measured ET+DS = 88% to 110%

	Drainage			
	Measured	Predicted	Error	
Cell No.	(% precip)	(% precip)	(% precip)	%
4	17.2	22.5	5.3	31
5	6.5	19.2	12.7	195
6	3.5	19.2	15.7	449
7	23.7	16.6	-7.1	-30
Mean	12.7	19.4	6.7	161
Std. Dev	9.4	2.4	10.2	214

Mean Error as Percent
of Mean Measured Drainage = 52.8%

Range in Measured Drainage as Percent
of Mean Measured Drainage = 28% to 187%

actual measurements was generally equal to about one-half the standard deviation of the measured values, indicating fairly good agreement.

The variability between the actual measurements and the HELP predictions could be influenced by a number of factors in the field. Errors were present in the field measurements of runoff and leachate drainage due to short periods of pump and runoff system malfunction in the springs of 1973, 1974, and 1975. Also, errors may have been introduced by using precipitation measurements collected approximately 2 miles from the test site. This might explain the large discrepancy during July 1975 seen in both the cumulative and monthly runoff plots. Based on a comparison with nearby weather stations, the major storm responsible for this runoff was highly localized, so that the measured rainfall may not accurately represent rainfall at the test site. Other uncertainties were introduced in selecting parameter values to describe the extent of vegetative growth, leaf area index, winter cover factor, evaporative depth, soil and waste characteristics and degree of compaction.

As previously discussed, a significant amount of variability existed within each set of covered and uncovered cells. The major difference in cell construction within each set was depth of the waste layer and refuse conditioning (shredded or unprocessed). The HELP model indicated that a negligible difference in long-term water balance would result from a change in waste layer depth. Similarly, the effect of refuse conditioning on the long-term water balance was not expected to be significant, so the model did not attempt to differentiate between these two types of waste. Other factors that could influence this variability include random nonuniformities in soil characteristics, degree of compaction, surface weathering, and vegetative growth.

Monthly plots in Figures 29 through 36 show measured field runoff occurring throughout the winter compared to HELP predictions which show no runoff during this period but excessive runoff in April. These computed results are consistent with HELP methodology which stores all precipitation on the surface as snow when average temperatures are below freezing. Thus, when Wisconsin temperatures warmed in April, all precipitation stored by HELP at the surface was allowed to either run off or infiltrate. The measured data suggest that this methodology is not appropriate. Significant runoff did occur in the field throughout the extended periods of daily average below-freezing temperatures; therefore, the field runoff in April was significantly less than that predicted by HELP.

To assess the runoff curve numbers (CN's) chosen for these cells, the simulation runs were repeated numerous times, changing only the value of the CN. For each year of measured cell data (excluding the first 2 years), the HELP run which most closely matched the measured annual runoff volume was determined. These CN's were averaged for each cell. The questionable precipitation and runoff from the large storm in April 1975 was excluded from this analysis. The CN's determined in this manner for the first three covered cells were 83, 82, and 84--all very similar to the originally selected value of 84.4. However, the average best-fit CN for the fourth covered cell (Cell 8) was 92. A comparison between Cell 8 field measurements and the HELP prediction for CN = 92 is shown in Figure 37. The average best-fit CN's for the

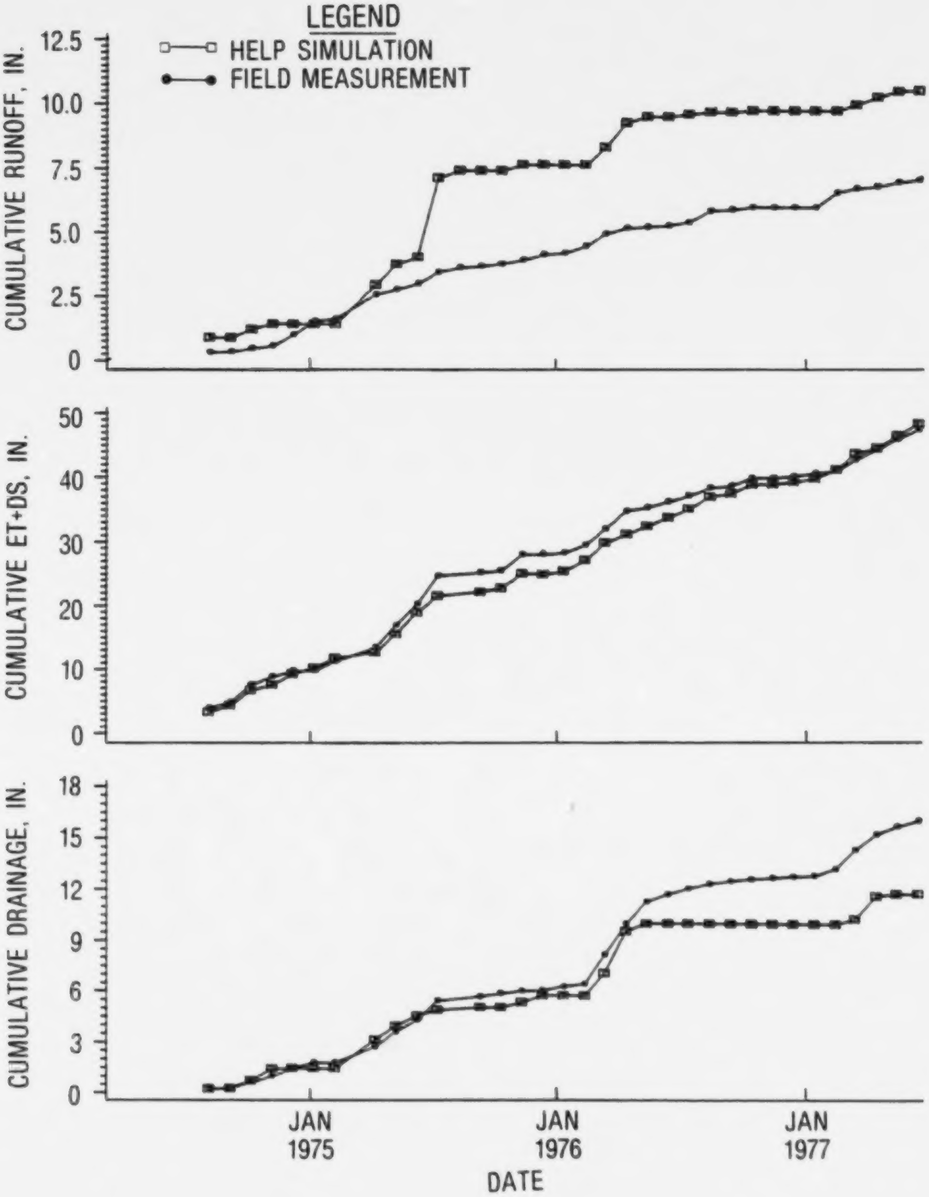


Figure 37. Field measurements for Cell 8 compared to HELP simulation for covered cells using CN = 92.

uncovered cells were all close to 86, higher than the originally selected value of 79. The field measurements from these cells are plotted with HELP predictions for CN = 86 in Figure 38.

A similar analysis was conducted to assess the hydraulic conductivity assumed for Layer 1 of the uncovered cells. This is the layer of waste that was subjected to surface weathering and vegetative growth. The simulation run for the uncovered cells (using CN = 86) was repeated numerous times changing only the hydraulic conductivity. The value of hydraulic conductivity which minimized the percent differences between field measurements and HELP predictions for runoff, ET+DS, and leachate drainage was selected as the best-fit hydraulic conductivity. These best-fit values were 0.14, 0.11, 0.11, and 0.08 inches/hour compared to the original value of 0.17 inches/hour.

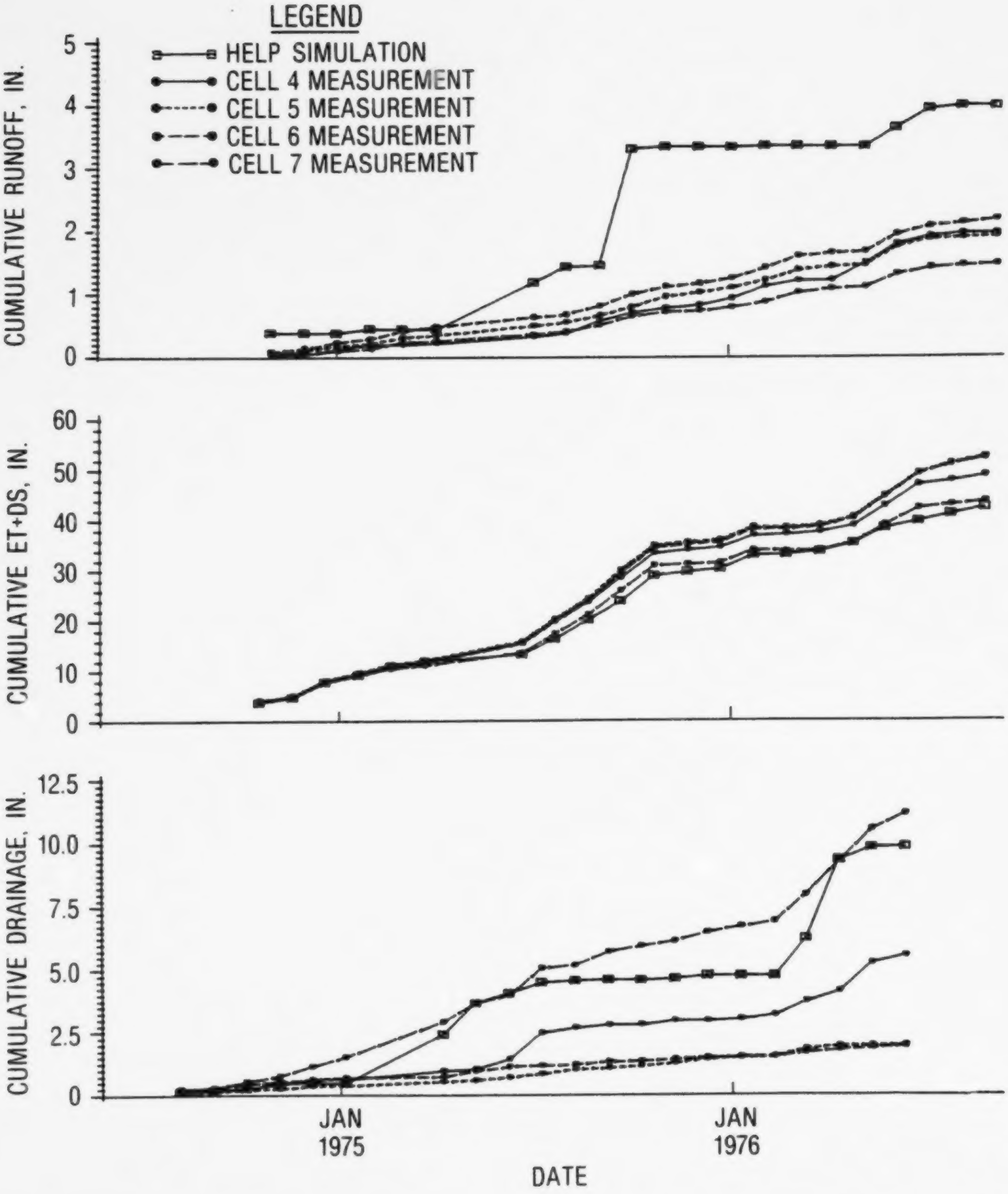


Figure 38. Field measurements for Cells 4, 5, 6 and 7 compared to HELP simulation for uncovered cells using CN = 86.

SECTION 7

SIMULATION OF SONOMA COUNTY TEST CELLS

A solid waste stabilization project was sponsored by the U.S. Environmental Protection Agency and Sonoma County, CA, from 1971 to 1974 (14). The purpose of the project was to investigate the stabilization of solid waste in five municipal sanitary landfill test cells by analyzing leachate, gas, temperature, and settlement parameters and to determine the effect on solid waste stabilization of applying excess water, septic tank pumpings, and recycled leachate. This section describes the simulation of these cells using the HELP model and presents comparisons between model predictions and field measurements.

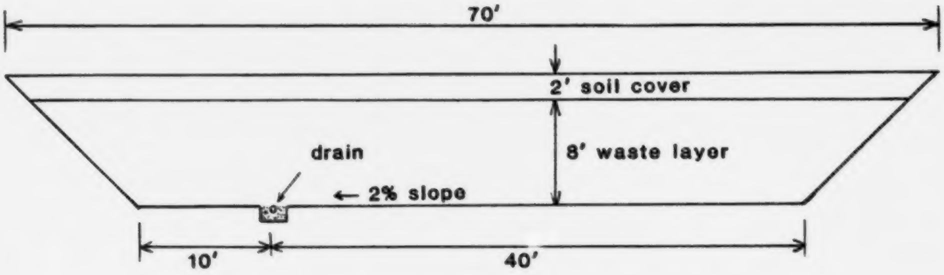
SITE DESCRIPTION

The test site is located in the southwestern portion of Sonoma County approximately 45 miles north of San Francisco. The mean temperature is 58°F, with the daily minimum temperature falling below freezing on 39 days per year. The mean annual precipitation is 31 inches. Ninety-five percent of this precipitation occurs from October to April. The mean daily solar radiation is approximately 410 langleys.

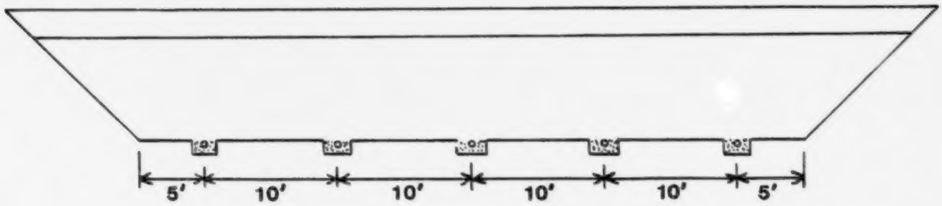
The cells were excavated in an area of sandy clay containing occasional thin layers of pervious waterbearing soils. When such pervious areas were encountered during cell excavation, the areas were overexcavated 2 feet and lined with compacted clay. Subsurface drains outside the cells were also installed where needed.

Cell dimensions presented in the remainder of this section were determined by roughly scaling them from figures in the stabilization project report (14) and therefore are approximate. The base of the cell in plan view is 50 feet square; 45-degree side slopes rise from each side of the base. Household refuse was placed directly on the clay base and compacted by a D-7 dozer in a manner similar to normal operations at a sanitary landfill. The depth of compacted refuse is 8 feet. All cells were capped with a 2-foot layer of native sandy clay soil.

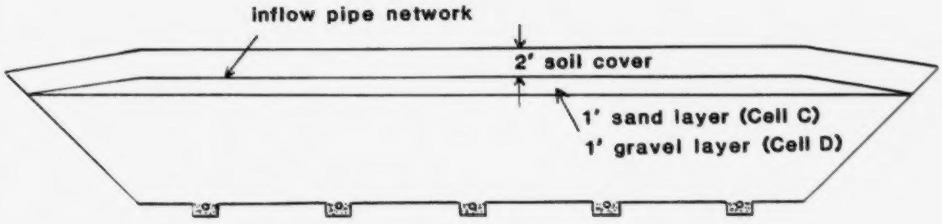
Other characteristics of cell configuration varied as shown in Figure 39. Operational characteristics are summarized in Table 12. Cells A, B, and E were constructed and operated as typical sanitary landfills except that the moisture content of the refuse was brought to field capacity prior to capping in Cell B by water and Cell E by septic tank pumpings. Cells C and D were


70'
2' soil cover
drain
8' waste layer
← 2% slope
10'
40'

a) CELLS A and E


5'
10'
10'
10'
10'
5'

b) CELL B


inflow pipe network
2' soil cover
1' sand layer (Cell C)
1' gravel layer (Cell D)

c) CELLS C and D

Figure 39. Cell dimensions for Sonoma County cells.

TABLE 12. SONOMA COUNTY CELL OPERATIONAL DESIGNS

Cell	Initial Application of Liquid	Continuous Application of Liquid
A	None	None
B	Water added to field capacity	None
C	None	Water added daily (200 to 1000 gal/day)
D	None	Recycled leachate added daily (500 to 1000 gal/day)
E	Septic tank pumpings added to field capacity	None

constructed with an inflow pipe network, and a sand/gravel distribution medium was installed between the waste layer and the soil cover. Water was continuously added to the waste through this network in Cell C, whereas landfill leachate was continuously recycled through the waste by the network in Cell D.

Leachate collection drains shown in Figure 39 diverted the leachate by gravity to collection tanks (Cells B, C, D) or to the nearby county landfill (Cells A and E). Standard house service water meters installed on the discharge lines of Cells A, C, D, and E measured the volume of leachate collected. Cell B leachate was measured with a graduated bucket as it was discharged from a collection tank. The frequency of meter readings and volume measurements varied but averaged about once per week.

SELECTION OF MODEL INPUT VALUES

Daily precipitation measurements made at the test site were used in the HELP simulations. Mean monthly temperatures taken from the NOAA Environmental Data Service for Santa Rosa, CA, (10 miles from the test site) were used. The solar radiation values used in the simulations were the default values for Sacramento incorporated in the HELP model.

Native clay at the site composed the landfill base, side slopes, and soil cover. In the stabilization project report (14), this soil was described as sandy clay and was identified as USCS soil class CL based on liquid and plastic limit tests. The HELP model default soil texture 14 was selected for use in the simulations since it represents CL soil and has a hydraulic conductivity similar to the USDA sandy clay classification as shown in Table 10 of the

HELP model user's guide. For the soil cover, soil texture 14 was selected to be treated as compacted during the simulations using the HELP model, since it was reported that "the sandy clay was spread in one-foot lifts and compacted by numerous passes of a D-7 dozer" (14). For the landfill base, or barrier soil layer, soil texture 14 was again treated as compacted, plus the hydraulic conductivity was changed to reflect the average of three in-place hydraulic conductivity tests (1.95×10^{-7} cm/sec or 0.000277 in./hr) reported for this barrier soil layer (14). The thickness of the barrier soil layer was set to 24 inches since this was the depth of clay liner replacement where pervious lenses were encountered during excavation.

Surface vegetation was assumed to be absent since (a) summer precipitation is inadequate to support significant vegetation, (b) no water balance accounting was made in the project report to include surface irrigation or sprinkling, and (c) the presence of surface vegetation was not addressed in the project report (14). Therefore, the vegetation type used in the HELP simulation was "bare ground" with year-round leaf area index values of zero and a winter cover factor of zero. The evaporative depth was chosen as 4 inches as suggested for bare ground by the HELP model.

SCS runoff curve numbers were estimated in two ways. First, the minimum infiltration rate method presented in Table 10 and Figure 4 of the HELP model documentation report (1) was used to determine a CN of 95. Second, individual storm rainfall and runoff data at the site were used to estimate CN values ranging from 88 to 98 with an average value of 95. Therefore, a CN of 95 was selected for the simulations. This calibration procedure is identical to that used for the University of Wisconsin-Madison data.

As previously described, Cells C and D had continuous inflow introduced into the landfill above the waste layer. To simulate these cells, the HELP computer code was modified to account for these inflows at the interface between the soil cover and the distribution medium. During operation of these cells, standard house service water meters measured the volume of inflow and were read approximately once per week. These volumes were input in the HELP simulation assuming a uniform distribution in time and over the landfill area. Since the evaporative zone depth was set to a value less than the soil cover depth, these inflows were not subjected to evapotranspiration losses in the HELP simulations. The parameter values chosen for the model are presented in Table 13.

RESULTS OF MODEL SIMULATIONS

Cells A, B, and E

Field monitoring began in November 1971, but a negligible leachate volume was produced in Cells A, B, and E until the following winter's rainy season. Therefore in the present study, the initial 12 months were treated as an equilibration period for the cells. A similar period was designated in the HELP simulations. Since the model must begin its simulation at the beginning of a calendar year, the period between January and November 1972 was used as an equilibration period for the model. These initial periods are not included in the following tables and figures.

TABLE 13. INPUT DATA FOR SIMULATION OF SONOMA COUNTY CELLS*

Parameter	Cells A and E	Cell B	Cell C	Cell D
No. of layers	4	4	5	5
Layer 1				
Thickness (in.)	24	24	24	24
Layer type	1	1	1	1
Soil texture	14	14	14	14
Is layer compacted?	Yes	Yes	Yes	Yes
Layer 2				
Thickness (in.)	72	72	12	12
Layer type	4	4	1	1
Soil texture	19	19	5	1
Is layer compacted?			No	No
Layer 3				
Thickness (in.)	24	24	72	72
Layer type	2	2	4	4
Soil texture	19	19	19	19
Layer 4				
Thickness	24	24	24	24
Layer type	3	3	2	2
Soil texture	14**	14**	19	19
Is layer compacted?	Yes	Yes		
Layer 5				
Thickness (in.)			24	24
Layer type			3	3
Soil texture			14**	14**
Is layer compacted?			Yes	Yes
Type of vegetation	Bare	Bare	Bare	Bare
SCS runoff curve no.	95	95	95	95
Evaporative depth (in.)	4	4	4	4
Surface area (sq ft)	4900	4900	4900	4900
Slope of lateral drainage (%)	2	2	2	2
Drainage length (ft)	40	5	5	5

* Input data terminology defined in the HELP model documentation (1) and user's guide (2).

** Hydraulic conductivity = 0.000277 in./hr based on permeability tests.

Cells A, B, and E were monitored for both surface runoff and lateral leachate drainage. Therefore, comparisons between model predictions and field measurements are presented for the following components of the water balance: (a) runoff; (b) the sum of evapotranspiration, change in landfill moisture storage, and barrier soil percolation (ET+DS+PERC); and (c) lateral leachate drainage. Field "measurements" of ET+DS+PERC were actually computed values based on the following relationship:

$$\text{ET+DS+PERC} = \text{PRCP} - \text{RNF} - \text{DRG} \qquad (29)$$

where PRCP = measured precipitation, RNF = measured runoff, and DRG = measured leachate drainage. Runoff from Cells A and E flowed into a single collection tank prior to measurement. It was assumed that Cells A and E contributed equally to this total measured runoff.

The field measurements for Cells A, B, and E are plotted together in Figure 40. The only differences in construction and operation of these cells were their initial refuse moisture content and the shorter lateral drainage length of Cell B. Since the first 12 months of data were treated as a period of equilibration and are not plotted, one would expect the remainder of the data to be somewhat similar. This was generally the case except for the leachate drainage measurements. The Sonoma County project report (14) was unable to explain these differences. However, a possible contributing factor was the manner in which soil cover shrinkage cracks were treated in the field. Soon after construction, the study investigators concluded that no leachate drainage would occur in Cells A, B, and E unless additional water was added. So shrinkage cracks which appeared in the soil cover during the first summer were deliberately left unsealed until the winter rains of 1972-73 infiltrated and eventually sealed the soil cover by natural swelling. Random variations in the size, timing, and patterns of the cracks may have influenced the erratic leachate drainage response.

Comparisons of cumulative runoff, cumulative ET+DS+PERC, and cumulative leachate drainage are plotted for Cells A, B, and E in Figures 41 through 43; monthly comparisons are plotted in Figures 44 through 46; and comparisons between predicted and measured values are summarized in Table 14. These results indicate that on the average for Cells A, B, and E, runoff accounted for 61.0 percent (s = 2.7 percent) of the precipitation. The HELP model predicted 71.6 percent, yielding an error of 10.6 percent (s = 2.5 percent) of the precipitation or a relative error of 17 percent of the measured runoff. The measured ET+DS+PERC was 36.0 percent (s = 3.4 percent) of the precipitation while the predicted value was 26.8 percent. The model underpredicted by 9.2 percent (s = 3.4 percent) of the precipitation or 26 percent of the measured ET+DS+PERC. Leachate drainage accounted for 2.94 percent (s = 1.56 percent) of the precipitation while the model estimated 0.07 percent. The average error was -2.87 percent (s = 1.55 percent) of the precipitation, and the relative error was -98 percent of the measured leachate.

The obvious major discrepancy in these comparisons is related to lateral leachate drainage. The model predicted that practically all leachate would leave through barrier soil percolation rather than lateral drainage. This is consistent with the assumptions that the barrier soil layer is always

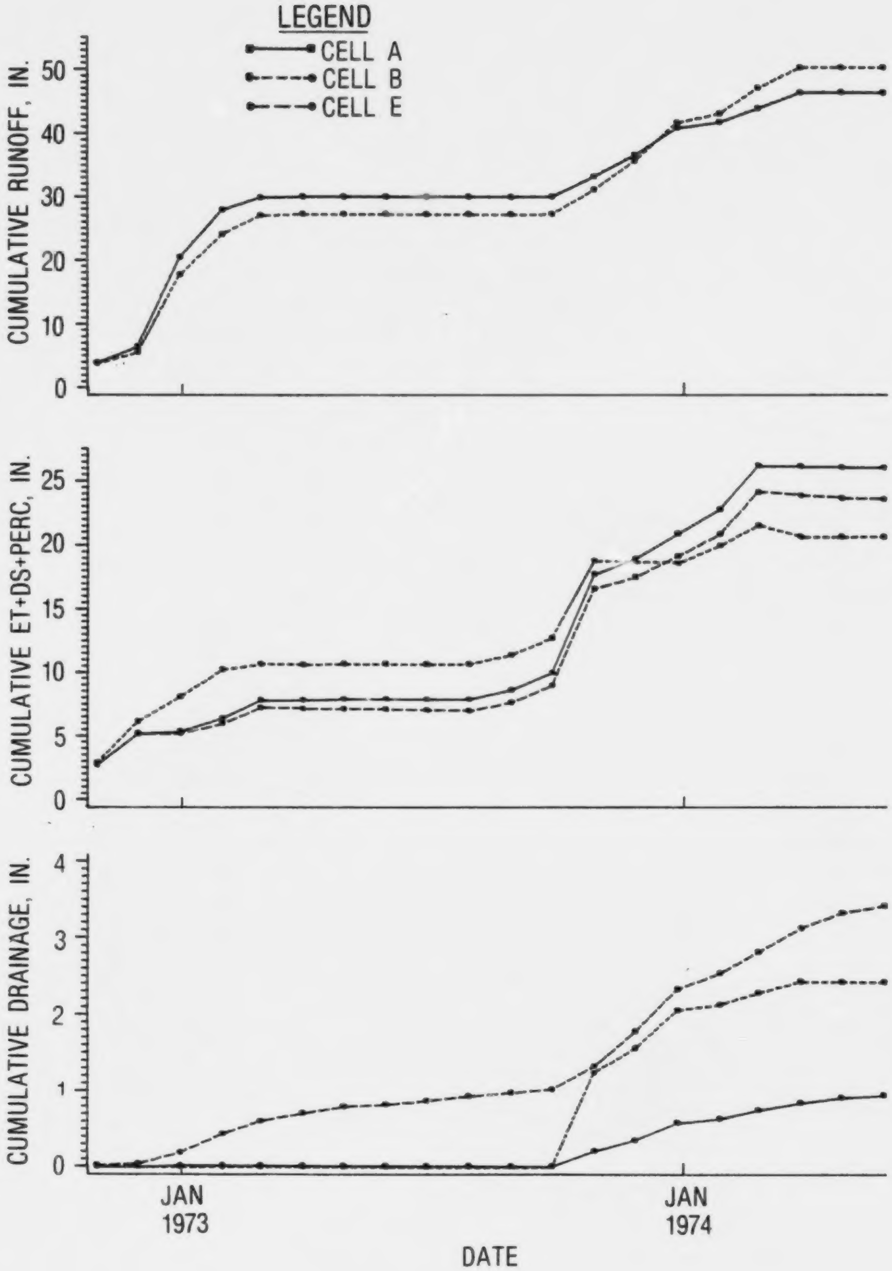


Figure 40. Field measurements for Cells A, B and E.

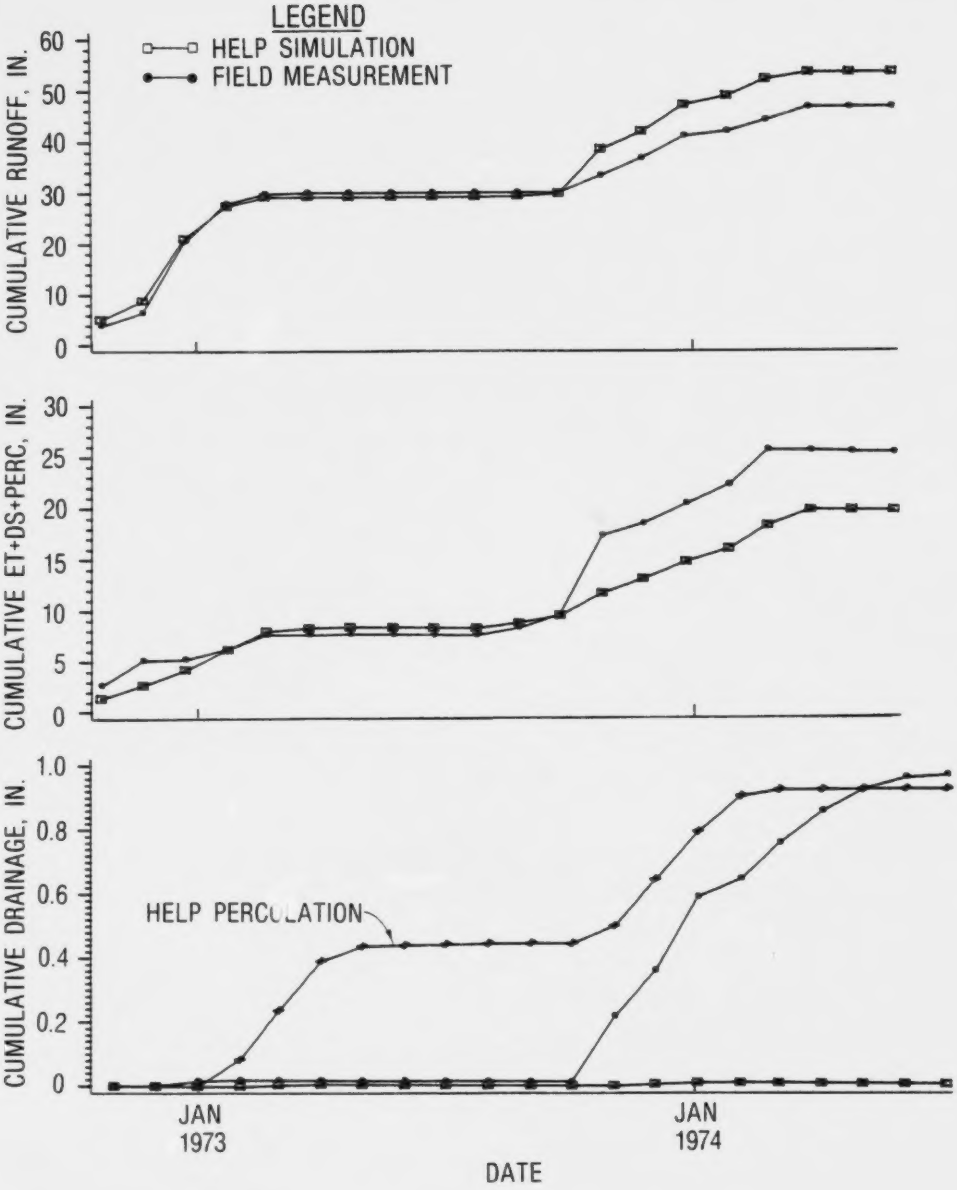


Figure 41. Field measurements for Cell A compared to HELP simulation; cumulative comparisons.

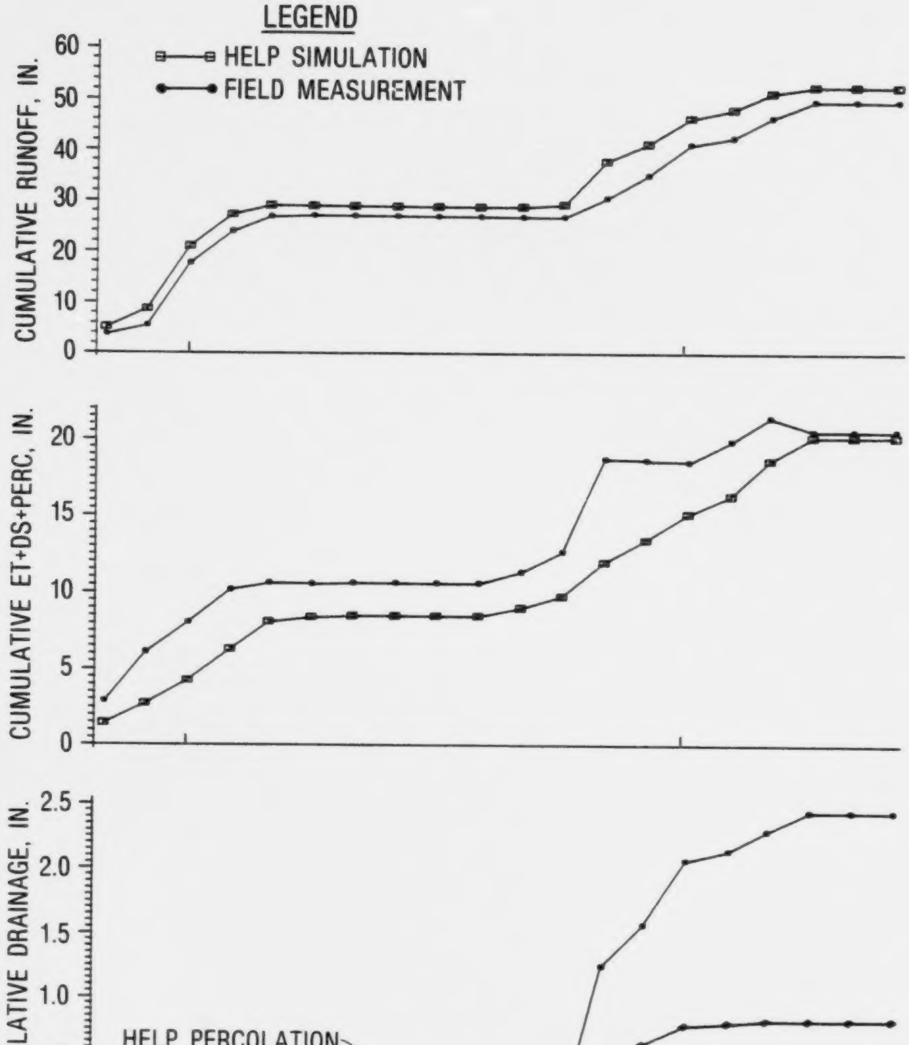


Figure 42. Field measurements for Cell B compared to HELP simulation; cumulative comparisons.

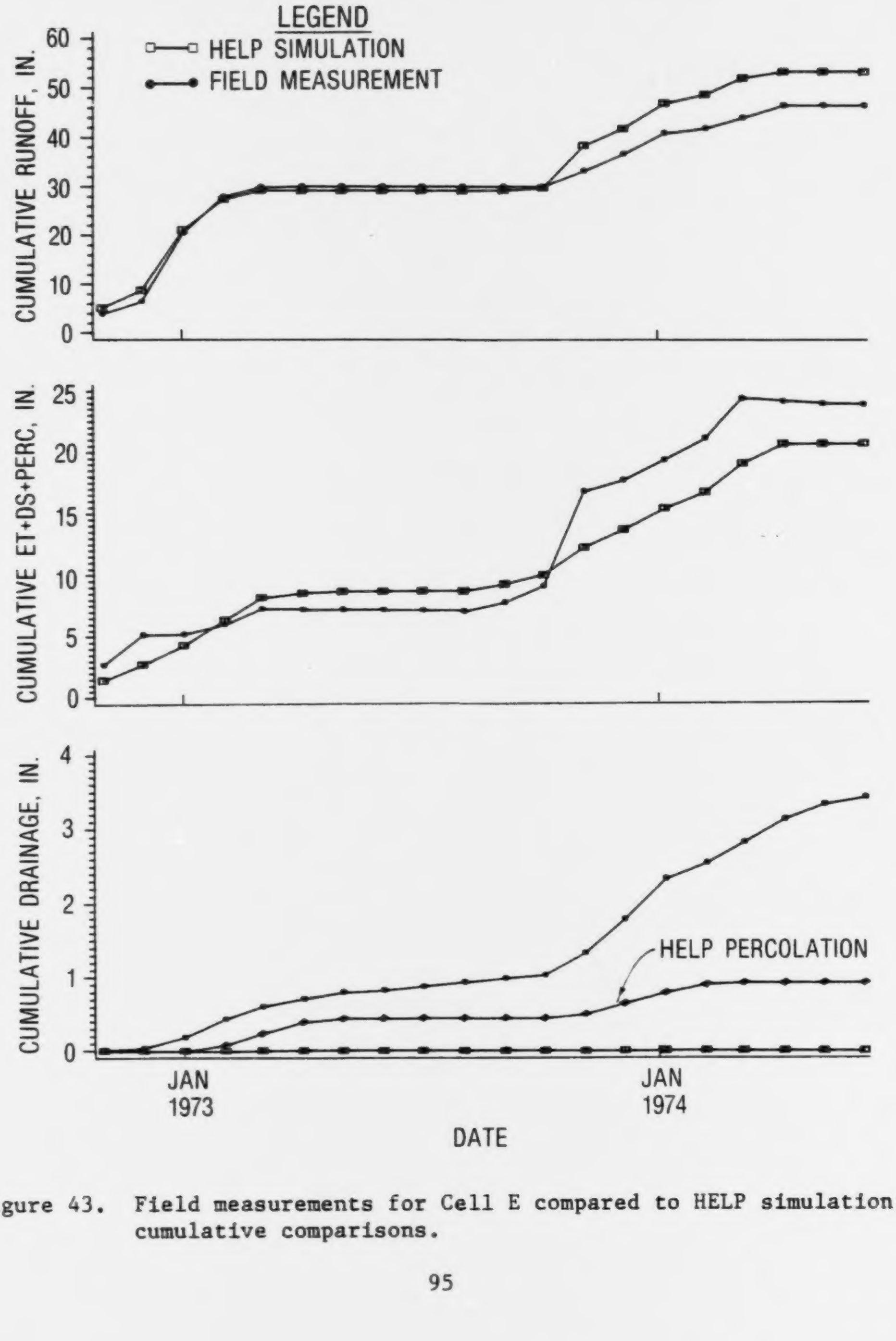


Figure 43. Field measurements for Cell E compared to HELP simulation; cumulative comparisons.

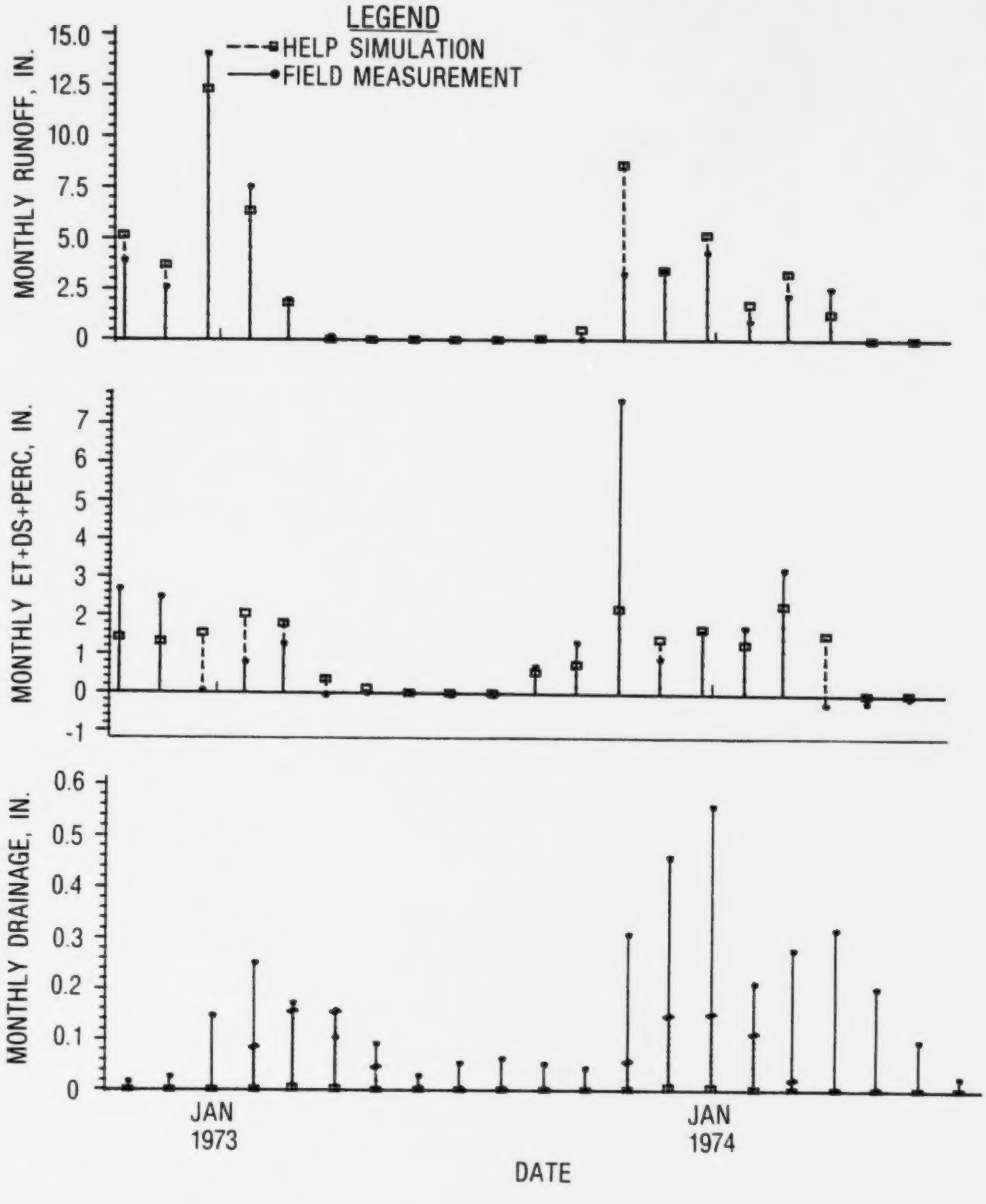


Figure 44. Field measurements for Cell A compared to HELP simulation; monthly comparisons.

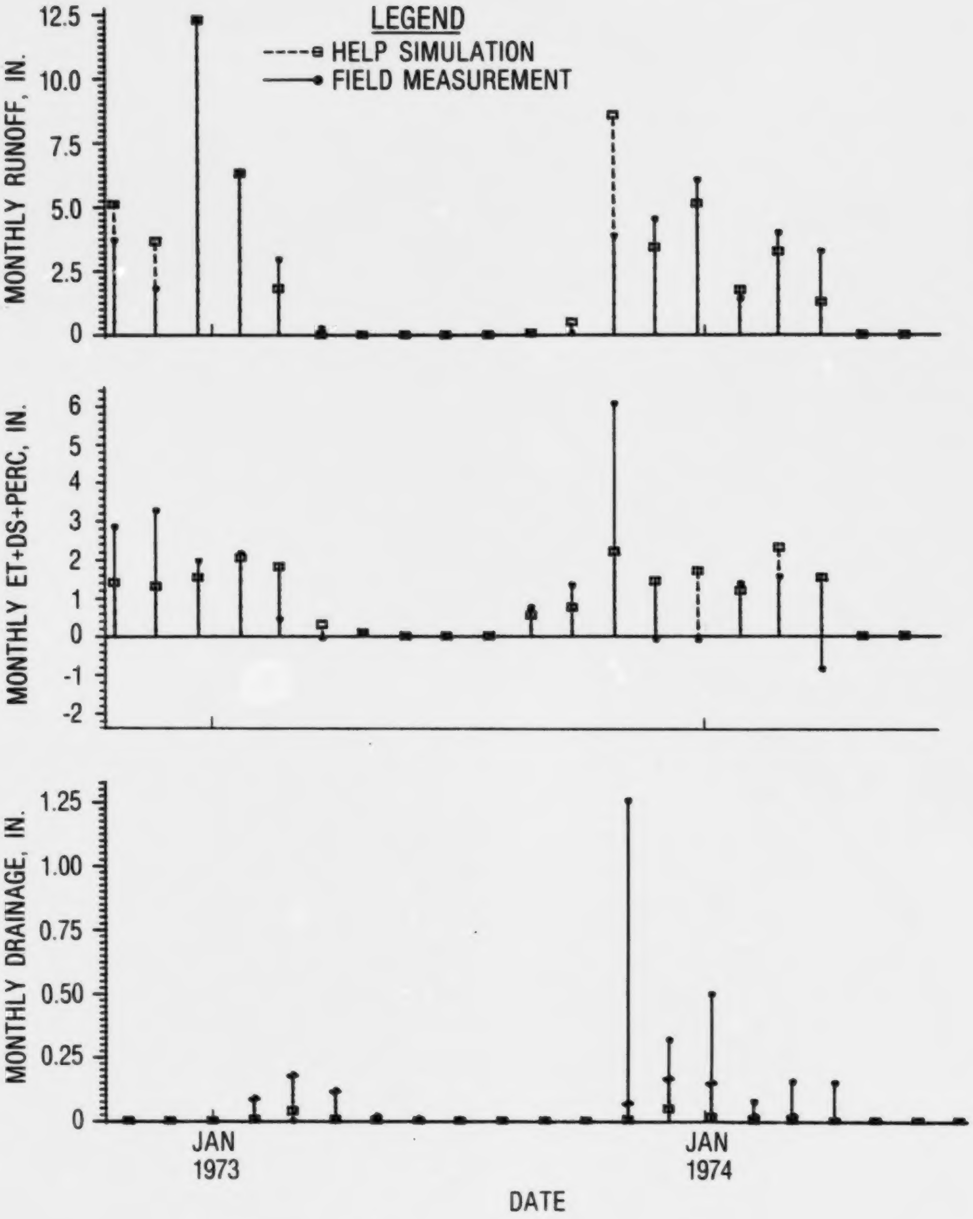


Figure 45. Field measurements for Cell B compared to HELP simulation; monthly comparisons.

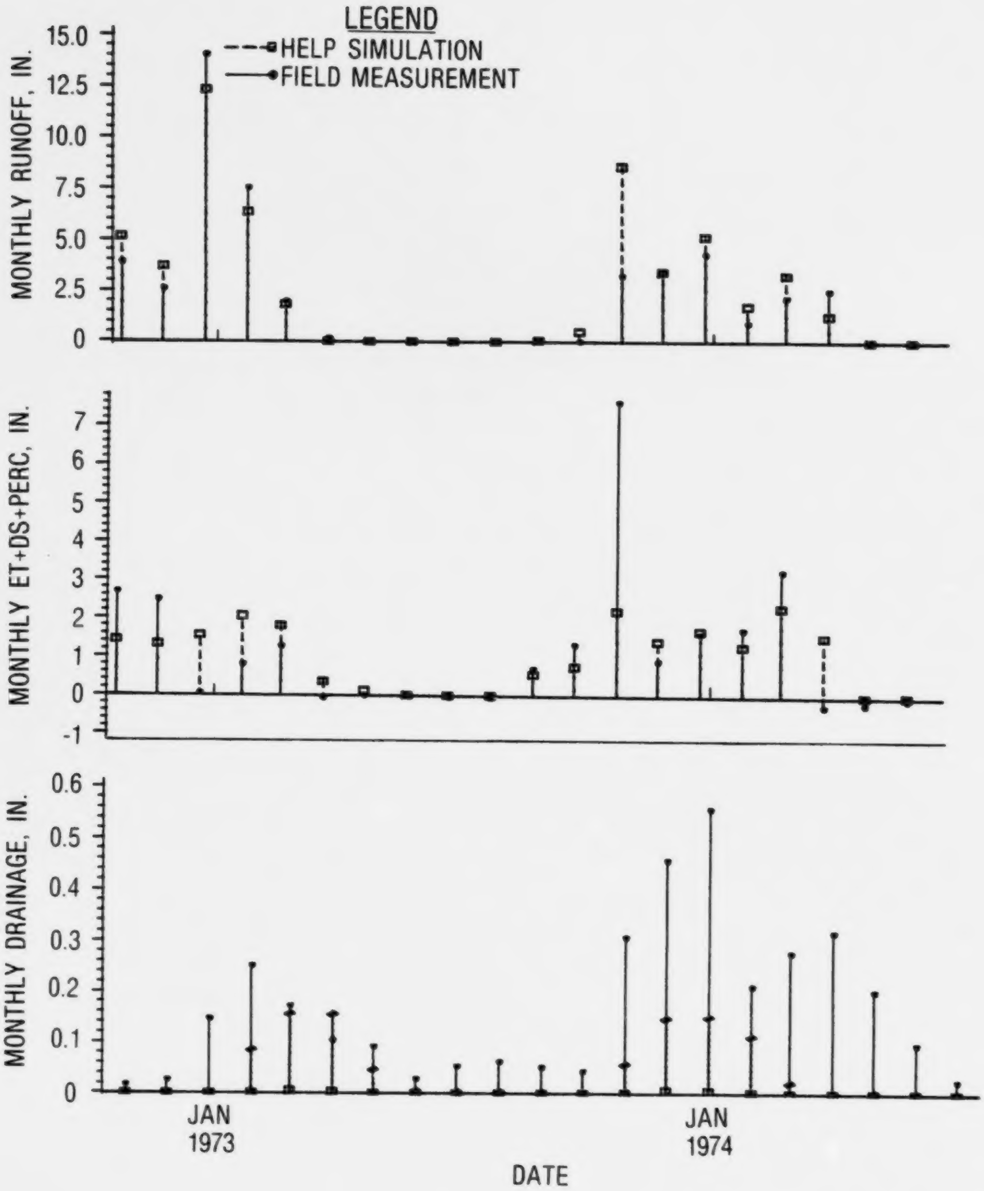


Figure 46. Field measurements for Cell E compared to HELP simulation; monthly comparisons.

TABLE 14. DIFFERENCE BETWEEN CUMULATIVE HELP MODEL PREDICTIONS AND CUMULATIVE FIELD MEASUREMENTS FOR SONOMA COUNTY CELLS

Runoff

Cell	Measured (% precip)	Predicted (% precip)	Error	
			(% precip)	(%)
A	59.3	71.9	12.6	21
B	64.1	71.9	7.8	12
C				
D				
E	59.7	71.1	11.4	19
Mean*	61.0	71.6	10.6	17
Std. Dev.*	2.7	0.5	2.5	5

Mean Error as Percent of Mean Measured Runoff = 17%*

Range in Measured Runoff as Percent of Mean Measured Runoff = 97% to 105%*

ET+DS+PERC

Cell	Measured (% precip)	Predicted (% precip)	Error	
			(% precip)	(%)
A	39.5	26.9	-12.6	-32
B	32.7	26.9	-5.8	-18
C				
D				
E	35.9	26.7	-9.2	-26
Mean*	36.0	26.8	-9.2	-25
Std. Dev.*	3.4	0.1	3.4	7

Mean Error as Percent of Mean Measured ET+DS+PERC = -26%*

Range in Measured ET+DS+PERC as Percent of Mean Measured ET+DS+PERC = 91% to 110%*

Drainage

Cell	Measured (% precip)	Predicted (% precip)	Error	
			(% precip)	(%)
A	1.26	0.03	-1.23	-98
B	3.21	0.15	-3.06	-95
C	314.49	380.25	65.76	21
D	996.53	989.85	-6.68	-1
E	4.35	0.03	-4.35	-99
Mean*	2.94	0.07	-2.87	-97
Std. Dev.*	1.56	0.07	1.55	2

Mean Error as Percent of Mean Measured Drainage = -98%*

Range in Measured Drainage as Percent of Mean Measured Drainage = 43% to 148%*

---

* Computed for Cells A, B, and E only.

saturated and that Darcy's law can be used to describe vertical percolation through this layer. These assumptions are incorporated into Equation 26, rewritten as

$$Q_P = A \bar{y} + K_P \tag{30}$$

where Q_P is the vertical percolation; A is a constant; $\bar{y}$ is the head above the barrier soil layer; and K_P is the saturated hydraulic conductivity of the barrier soil layer. Equation 30 is solved simultaneously with Equation 25 to describe both vertical percolation and lateral flow through a lateral drainage layer. When the slope, drainage length, and saturated hydraulic conductivity of the drainage layer are specified, Equation 25 reduces to

$$Q_D = B \bar{y}^{2.16} + C \bar{y} \tag{31}$$

where Q_D is the lateral flow, and B and C are constants. Therefore when $\bar{y}$ approaches zero, Q_D approaches zero while Q_P approaches the saturated hydraulic conductivity of the barrier soil layer. In the case of Cells A, B, and E, the model input values described a system that produced very small heads such that $Q_P \gg Q_D$. The large discrepancy between predicted and measured Q_D in these cells implies that either the HELP methodology for dividing flows between Q_P and Q_D may not be appropriate for very small volumes of inflow or the model input values were not appropriate. Since no data exist for evaluating Q_P and Q_D with small inflows, the following discussion focuses on the choice of model input values. Results are presented only for cells A and E.

First, default soil characteristics for one additional CL soil, soil texture 15, are available in the HELP model. Figure 47 shows the results of using this soil texture (compacted) for the soil cover and for the barrier soil whose hydraulic conductivity remained 0.000277 in./hr (1.95×10^{-7} cm/sec). This soil texture produced a greater deviation from measured values, reducing predicted leachate drainage from an average of 1.5 percent to an average of less than 0.1 percent of the measured drainage.

Also, the average of the three barrier soil hydraulic conductivity tests may not be representative, especially in view of the large percolation volumes predicted by the model. Figure 48 shows the results using the lowest of the three measured hydraulic conductivities, 0.000094 in./hr (6.6×10^{-8} cm/sec), for the barrier soil. Although this change reduced percolation and increased drainage to a small degree, percolation still dominated, and drainage remained only a small fraction of the measured value.

Additional runoff curve numbers were also used in an attempt to match predicted and measured runoff. Figure 49 presents a plot of the model results using a CN of 60 instead of 95. This change had a negligible effect on predicted runoff, indicating that CN alone was not controlling runoff.

It was difficult to determine from the project report (14) the degree of compaction of the soil cover. Figure 50 shows the results using soil

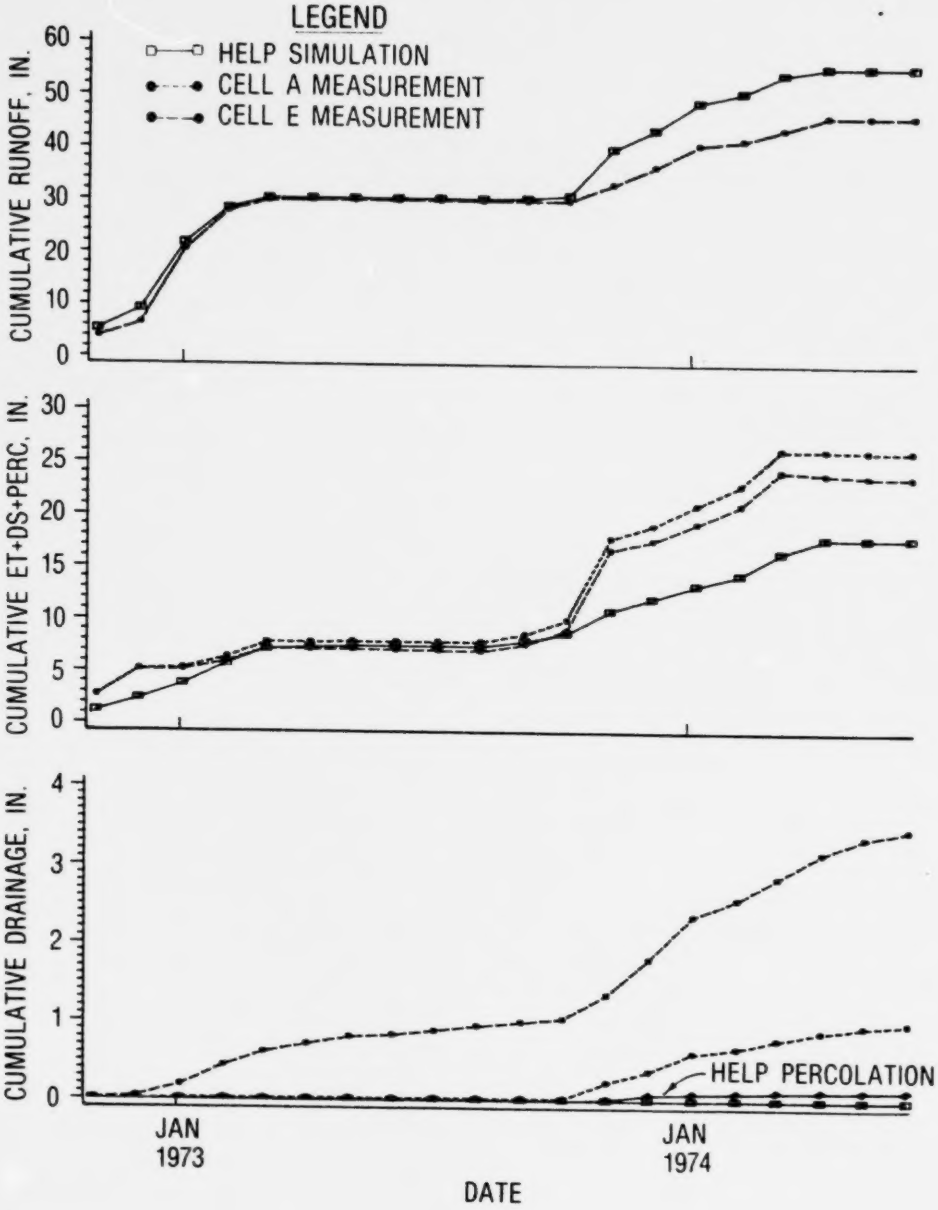


Figure 47. Field measurements for Cells A and E compared to HELP simulation using default soil texture 15 for topsoil.

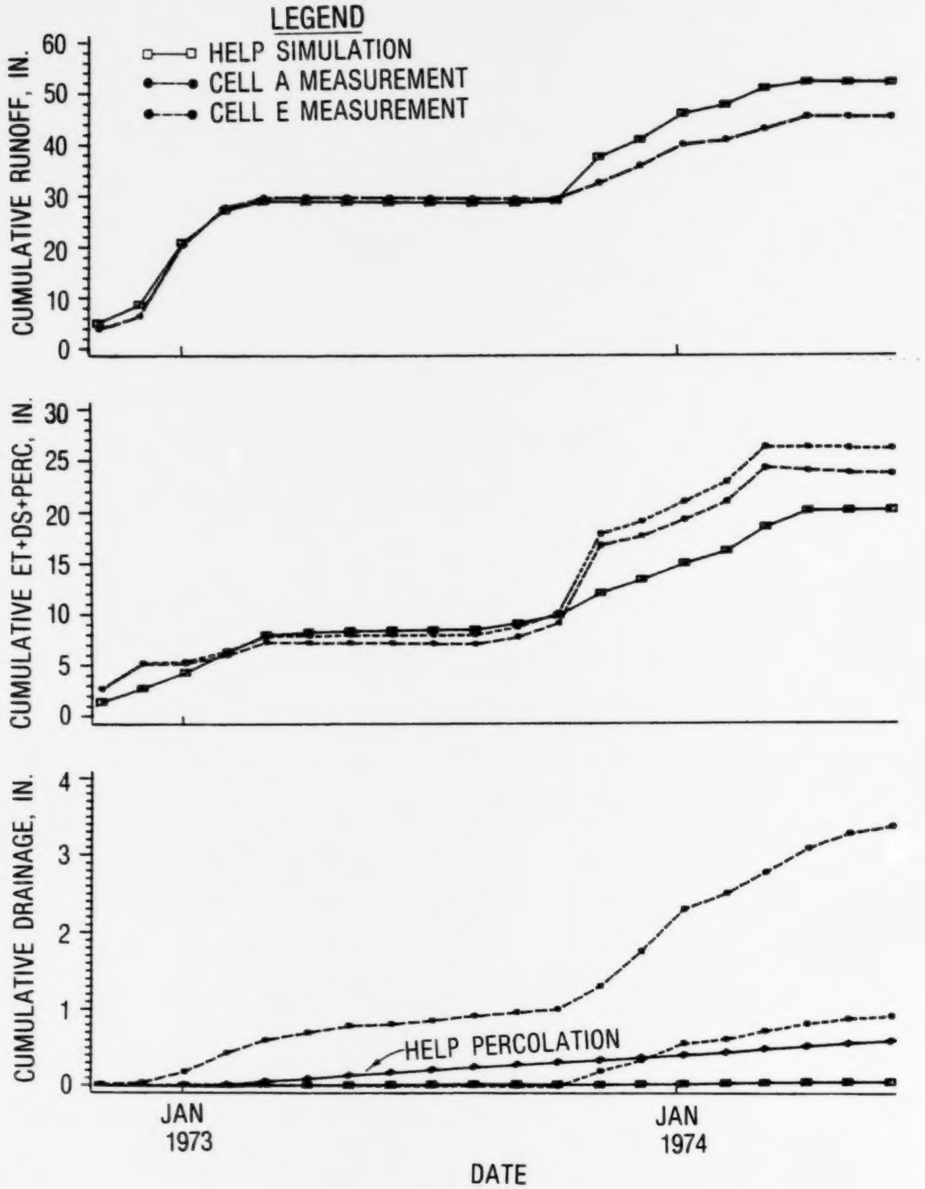


Figure 48. Field measurements for Cells A and E compared to HELP simulations using a barrier soil hydraulic conductivity of 0.000094 in./hr.

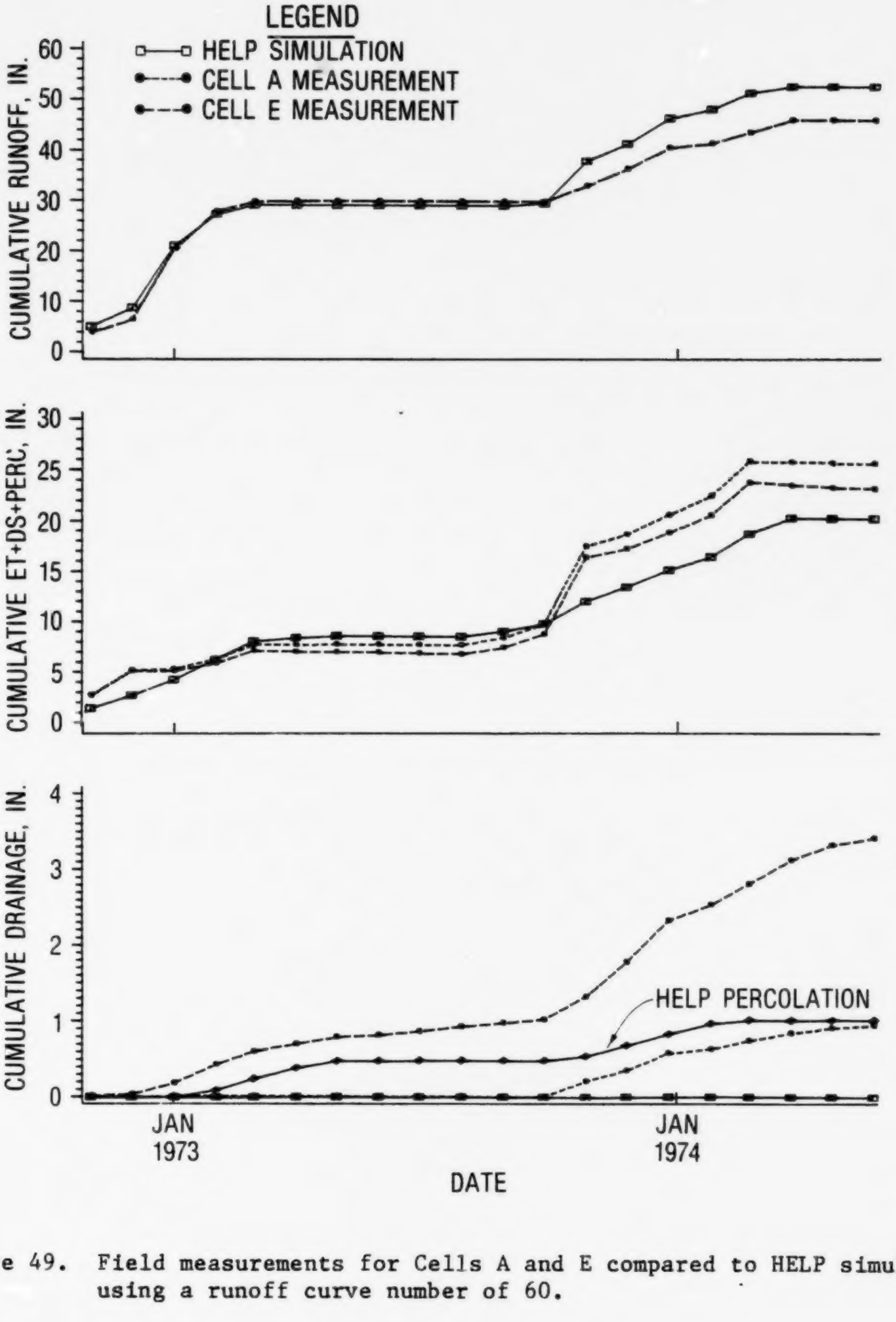


Figure 49. Field measurements for Cells A and E compared to HELP simulation using a runoff curve number of 60.

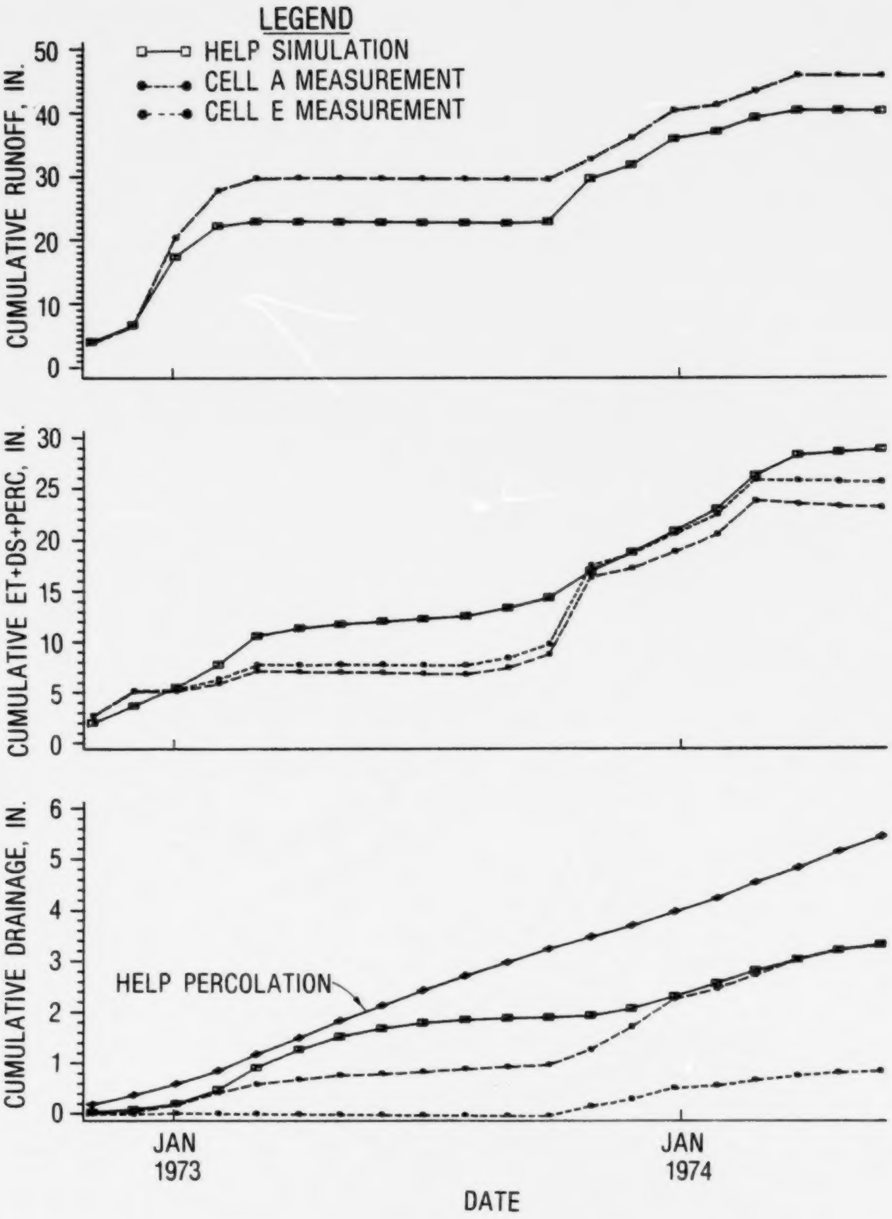


Figure 50. Field measurements for Cells A and E compared to HELP simulation using 25-percent compaction for topsoil.

characteristics reflecting changes equal to 25 percent of the magnitude of changes predicted by the HELP model due to compaction. That is, the wilting point remained constant, the plant available water and drainable porosity estimated for uncompacted soil were both reduced by 6.25 percent, the hydraulic conductivity was divided by 5.0, and the evaporation coefficient was set to 3.7. In this case runoff decreased, allowing more rainfall to infiltrate without an equally compensating increase in evapotranspiration so that predicted leachate drainage exceeded the measured value. This implies that perhaps the actual effects of compaction is between the 25 percent level and full compaction as defined by the HELP model. This was explored further by varying the hydraulic conductivity of the soil cover between 0.00325 in./hr (2.3×10^{-6} cm/sec) representing 100 percent of the effects of compaction and 0.06500 in./hr (4.6×10^{-5} cm/sec) representing no compaction. The hydraulic conductivity that matched measured leachate drainage the closest was between 0.00727 and 0.01190 in./hr (between 5.1×10^{-6} and 8.4×10^{-6} cm/sec).

Finally, the evaporative depth was varied to determine its effect on the predicted results. Increasing the evaporative depth from 4 to 24 inches reduced the predicted runoff from about 120 percent to about 114 percent of measured runoff, while predicted ET+DS+PERC increased from about 71 percent to about 84 percent of measured ET+DS+PERC. Predicted leachate drainage was reduced to zero.

Cells C and D

As previously described, Cells C and D contained a distribution pipe network beneath the soil cover. A continuous inflow of liquid above the waste layer was thus introduced which was assumed to be protected from evapotranspiration losses. The average annual inflow was approximately 141 inches for Cell C and 355 inches for Cell D. This inflow would be expected to control the response of leachate drainage and barrier soil percolation since rainfall alone produced only a few inches of leachate drainage per year in Cells A, B, and E. Because of this large volume of inflow, no equilibration period was deleted from the comparisons that follow.

Inflow volume and lateral leachate drainage were the only variables measured in the field for Cells C and D. Measurements show that at least 18 percent of the inflow did not appear in leachate drainage for Cell C and at least 4 percent did not appear in Cell D. This unaccounted volume could be due to barrier soil percolation, leakage through a failed portion of the clay liner, measurement errors, or evaporation through shrinkage cracks in the soil cover. Of these sources, the HELP model can only simulate barrier soil percolation.

Comparisons between predicted and measured leachate drainage are contained in Figures 51 and 52 for cumulative volume and Figures 53 and 54 for monthly volume. HELP model predictions for runoff and ET+DS+PERC are also included. Percent differences are summarized in Table 14. The comparisons show that the HELP model overpredicted leachate drainage by 21 percent for Cell C and by 1 percent for Cell D. Since the Cell D simulation appears to be very accurate and since construction plans for Cells C and D were identical, it is assumed that most of the excess drainage predicted by the HELP model for

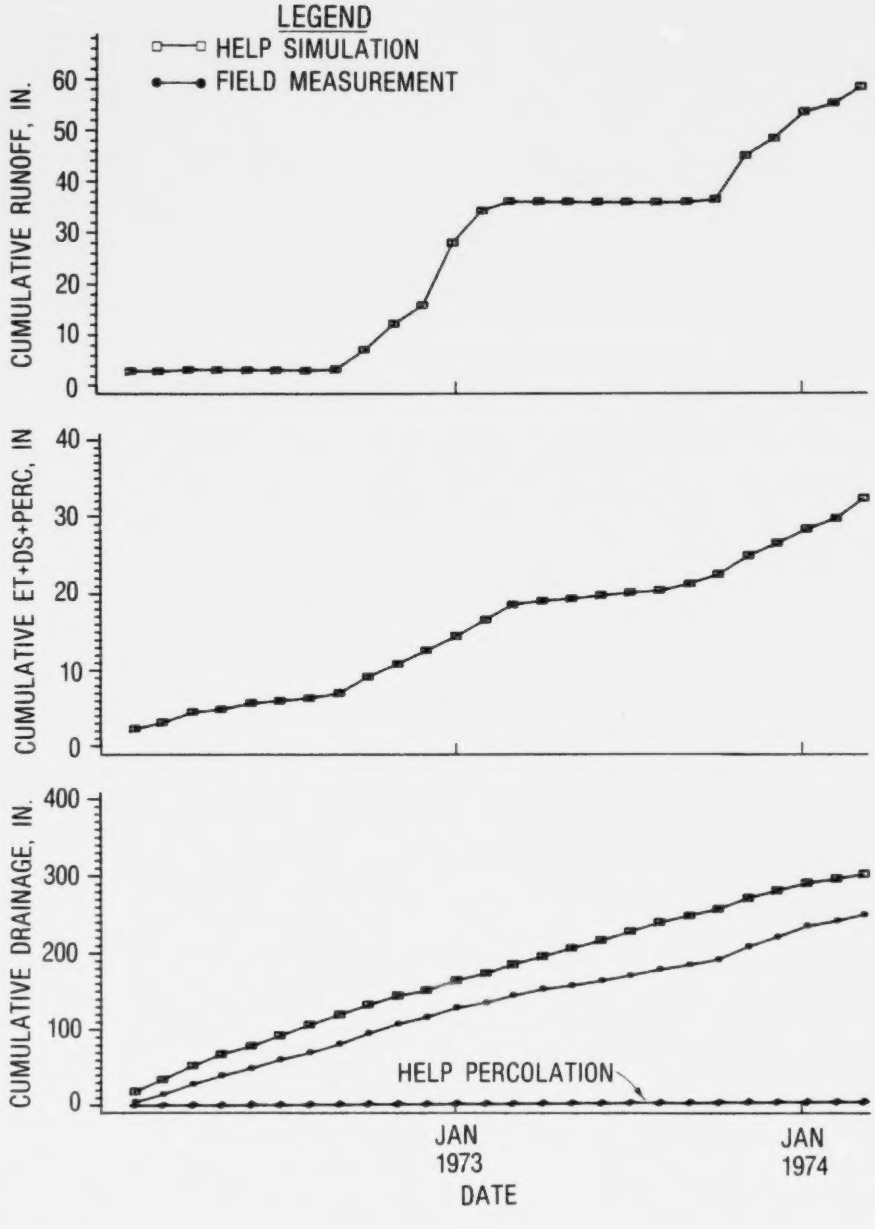


Figure 51. Field measurement of leachate drainage for Cell C compared to HELP simulation; cumulative comparison.

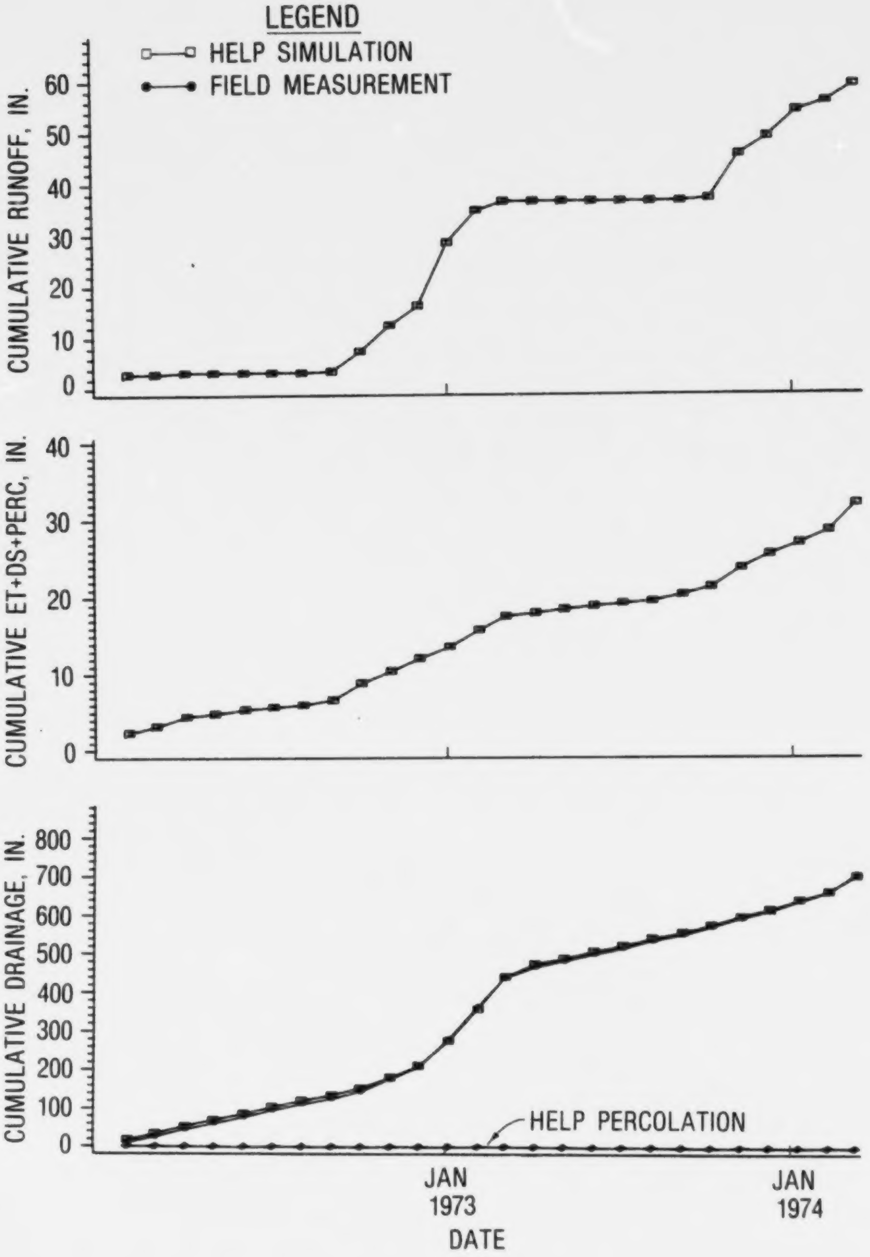


Figure 52. Field measurement of leachate drainage for Cell D compared to HELP simulation; cumulative comparison.

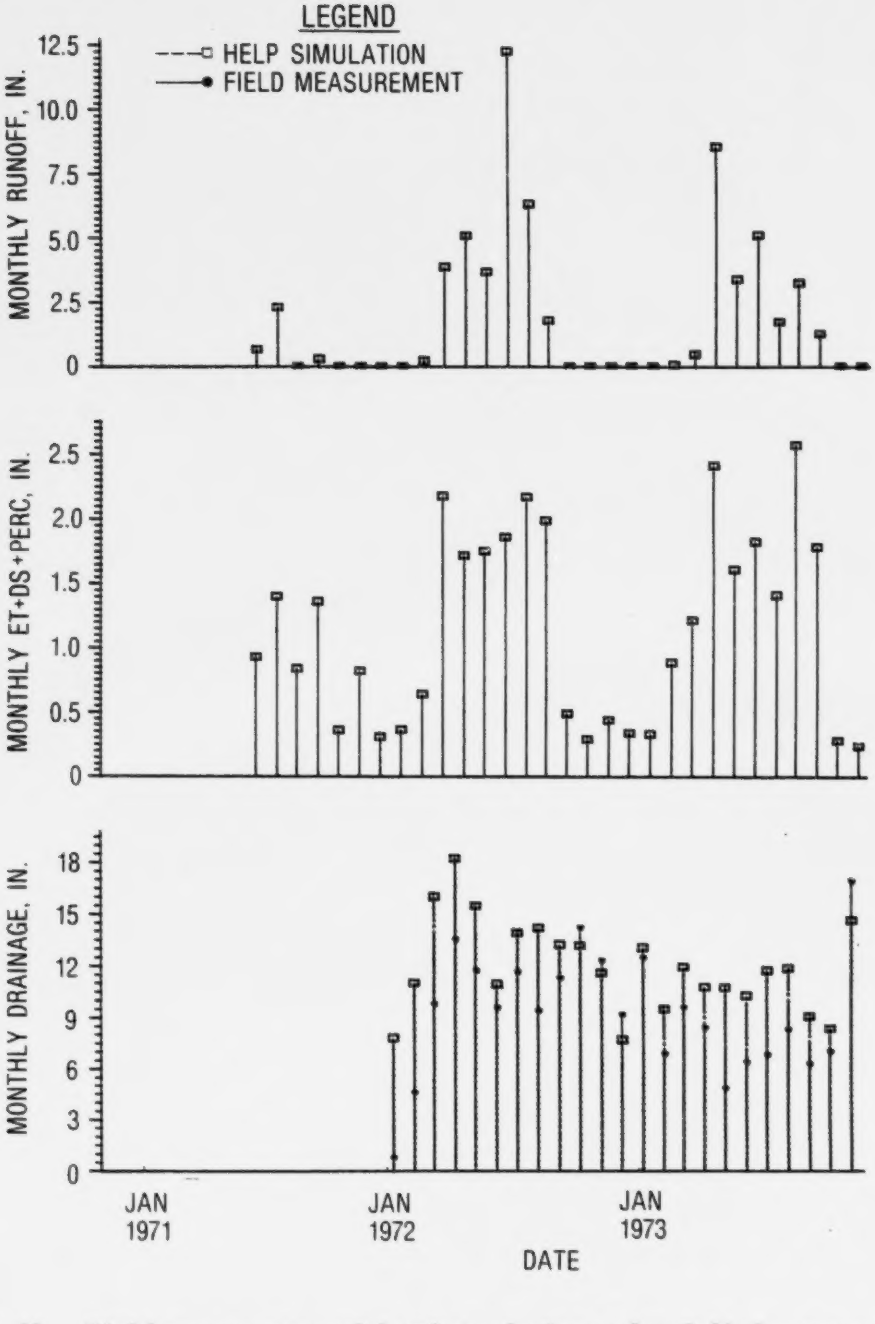


Figure 53. Field measurement of leachate drainage for Cell C compared to HELP simulation; monthly comparison.

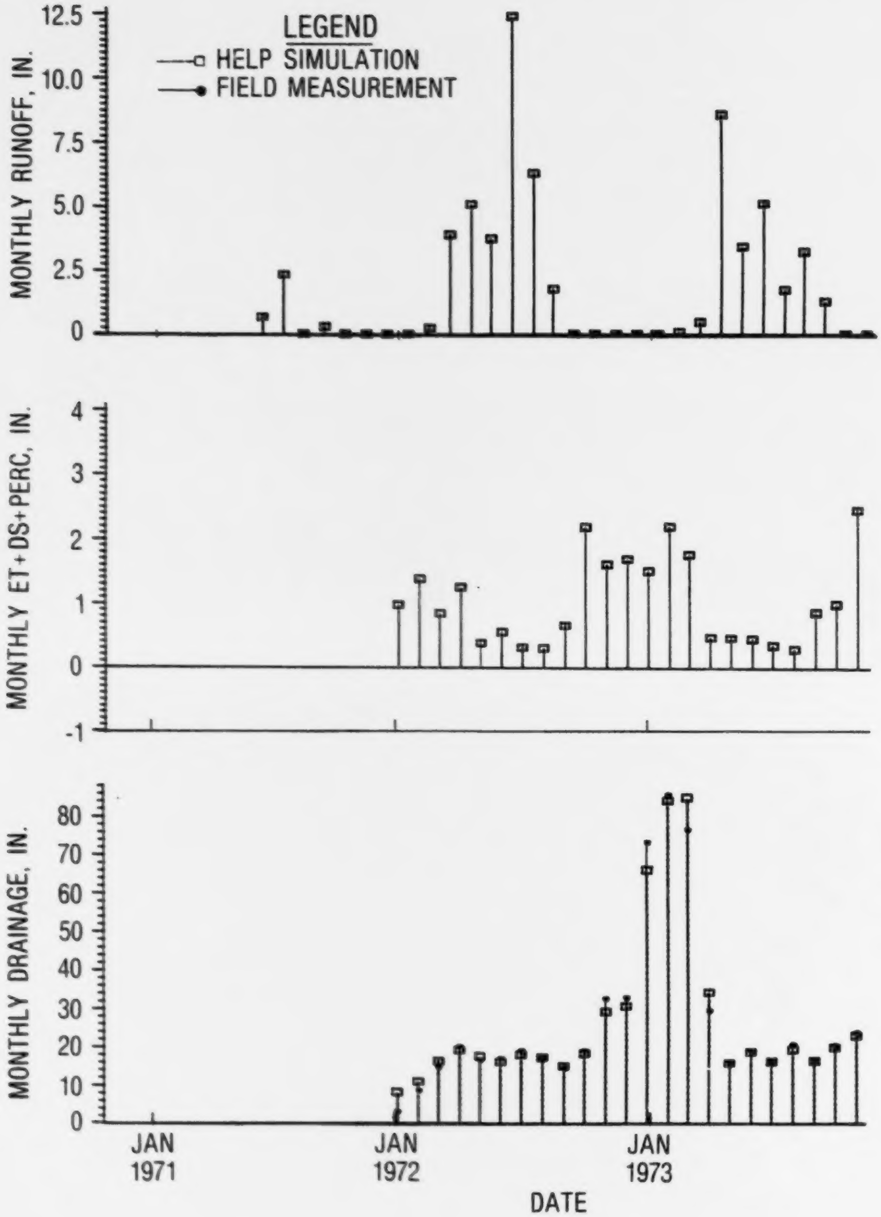


Figure 54. Field measurement of leachate drainage for Cell D compared to HELP simulation; monthly comparison.

Cell C was actually lost through sources other than lateral drainage or barrier soil percolation.

Based on measurements of leachate drainage in Cells A, B, and E, rainfall accounted for about 1 percent or less of the leachate drainage in Cells C and D. This provides a unique test of the HELP model methodology for dividing flow between lateral drainage and vertical percolation since inflows and lateral drainage outflows are both essentially known. The excellent reproduction of Cell D drainage appears to confirm the appropriateness of the HELP model methodology for large inflows.

SECTION 8

SIMULATION OF BOONE COUNTY TEST CELL

Two field-scale test cells and three small-scale cells were studied from 1971 to 1980 in Boone County, KY, under the sponsorship of the U.S. Environmental Protection Agency (15,16). The study objectives were to evaluate the amount and characteristics of leachate, the composition of gases, the temperature conditions, the settlement of the cells, and the efficiency of the clay liner, and to compare the behavior between the field-scale and small-scale cells. The data collected from one of the field-scale cells were determined suitable for a HELP simulation study which is reported in this section.

SITE DESCRIPTION

The test site is located in Boone County approximately 20 miles south of Cincinnati, Ohio. The mean annual temperature is 54°F, with the daily minimum temperature falling below freezing on 111 days per year. The mean annual precipitation is 43 inches. The mean daily solar radiation is approximately 360 langleys.

The test cell shown in Figure 55 consisted of a 30-foot-wide by 150-foot-long trench with vertical walls and ramps on both ends sloping at 14 percent. The middle 50 feet were sloped at 7 percent to the transverse centerline. Since the base of the excavation consisted of fractured limestone, an additional depth of 0.5 foot was excavated and replaced with compacted native clay. A 30-mil synthetic liner, 30 feet wide by 50 feet long, was centered over the base of the cell. A leachate collection pipe embedded in gravel was placed on the synthetic liner at the bottom of the cell. An 18-inch-thick compacted clay liner was placed over the synthetic liner and collection pipe. This liner was found to have an average in-place hydraulic conductivity of 4.0×10^{-7} cm/sec at the conclusion of the test cell study. A second pipe was embedded in a gravel-filled section of the clay liner directly above the lower pipe as shown in Figure 55 to collect lateral leachate drainage above the clay liner. A 6-mil polyethylene strip was placed beneath this pipe to prevent leachate from short-circuiting to the lower pipe. Residential refuse was placed and compacted above this liner system, and a 2-foot layer of cover soil was deposited onto the completed waste layer. The cover soil was identified as USCS soil class CL and was found to have an average in-place hydraulic conductivity of 5.0×10^{-5} cm/sec at the conclusion of the test cell study.

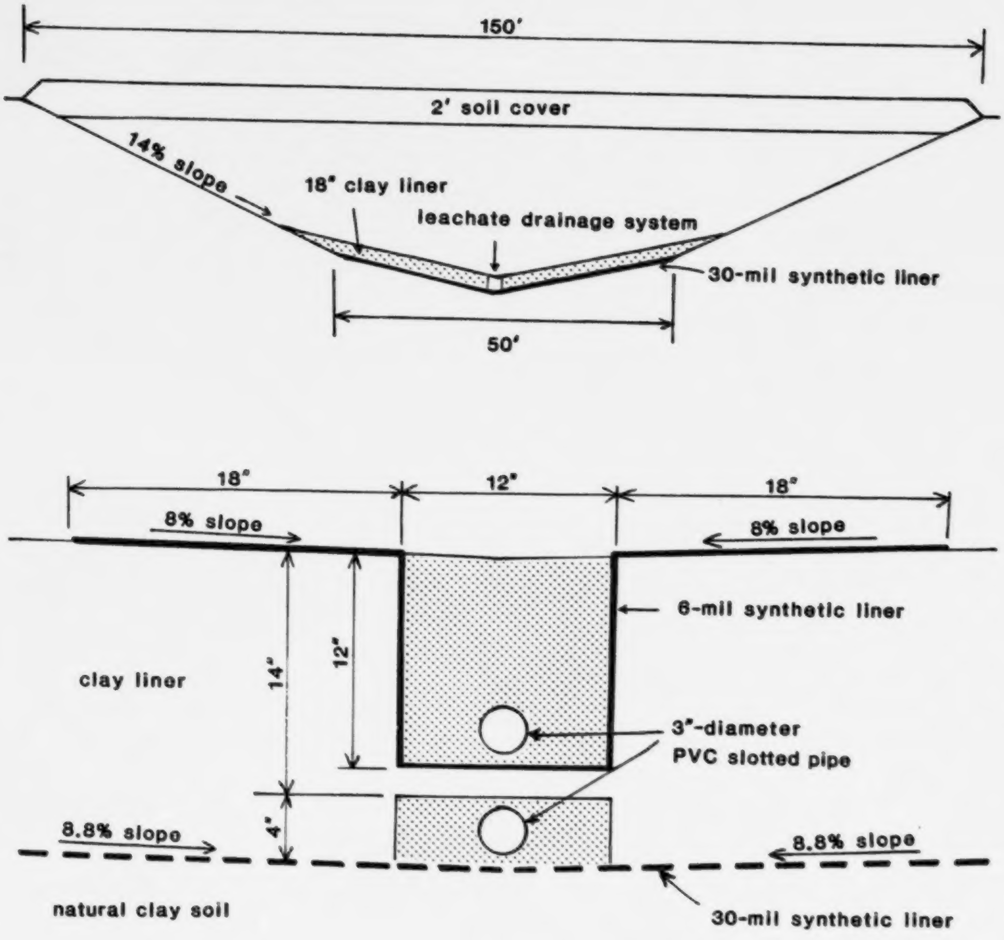

150'
2' soil cover
14% slope
18" clay liner
leachate drainage system
30-mil synthetic liner
50'
18"
12"
18"
8% slope
8% slope
6-mil synthetic liner
clay liner
14"
12"
3"-diameter
PVC slotted pipe
4"
8.8% slope
8.8% slope
natural clay soil
30-mil synthetic liner

Figure 55. Cell dimensions for Boone County cell.

SELECTION OF MODEL INPUT VALUES

Precipitation at the test site was recorded once or more per week throughout the study period. These values were used to adjust daily precipitation records from the nearest NOAA weather station, located approximately 15 miles away at Covington, KY. The adjustments were made by multiplying each daily value by the ratio of total monthly precipitation at the test site to total monthly precipitation at Covington. Mean monthly temperatures were taken from the Covington weather station. Solar radiation values were the default values for Cincinnati incorporated in the HELP model.

Default soil texture 14 was chosen to describe the 2-foot topsoil layer. This texture matches the CL classification for this topsoil and has a hydraulic conductivity close to that measured for this layer.

To model the circuitous path of clay liner percolation, an equivalent liner thickness of 12 feet was chosen. The area of the gravel packing/clay liner interface surrounding the lower pipe was treated as a leakage opening through a synthetic membrane. The leakage fraction was computed as the area of this interface divided by the area of the clay liner/waste layer interface, or about 0.03. The measured in-place hydraulic conductivity of the clay liner was used in the HELP simulations along with the remaining values for default soil texture 20.

The surface vegetation was assumed to be fair grass based on reported observations at the end of the test cell study indicating abundant fine grass roots in the top 7 to 8 inches of soil cover. An evaporative depth of 7.5 inches was selected to correspond with this observation. A default runoff curve number of 85.7 was determined by the HELP model and used in the simulations. Table 15 summarizes the input parameter values for the Boone County test cell.

RESULTS OF MODEL SIMULATIONS

The test cell was monitored for both leachate drainage above the clay liner and leachate percolation through the clay liner. However, a number of factors could have influenced these measurements. First, the synthetic liner beneath the clay base only extended to the edge of the 14-percent side slopes. The project report (15) states that the 14-percent slope was steep enough to encourage water to flow down the ramps onto the liner without appreciable seepage loss. Nevertheless, this created the potential for losses, especially if leachate was ponded to depths greater than about 2 feet above the drainage pipe. Secondly, there appeared to exist a possibility of high water table conditions. Although the project report (15) did not directly address water table elevations, it discussed a second test cell located about 150 feet away in which measured drainage exceeded precipitation by 50 percent. The possible explanations given were surface water infiltration from outside the cell and groundwater seepage. Since the vertical sides of the test cell were not lined, any water table rise above the cell base could have resulted in groundwater inflow.

TABLE 15. INPUT DATA FOR SIMULATION OF BOONE COUNTY CELL*

Parameter	Value
No. of layers	4
Layer 1	
Thickness (in.)	24
Layer type	1
Soil texture	14**
Is layer compacted?	No
Layer 2	
Thickness (in.)	48
Layer type	4
Soil texture	19
Layer 3	
Thickness (in.)	24
Layer type	2
Soil texture	19
Layer 4	
Thickness (in.)	144
Layer type	5
Soil texture	20†
Liner leakage fraction	0.03
Type of vegetation	Fair
Evaporative depth	7.5
Surface area (sq ft)	4653
Slope of lateral drainage (%)	8
Drainage length (ft)	50

* Input data terminology defined in the HELP model documentation (1) and user's guide (2).

** Hydraulic conductivity = 0.071 in./hr or 5.0×10^{-5} cm/sec.

† Hydraulic conductivity = 0.00057 in./hr or 4.0×10^{-7} cm/sec.

Measurable leachate was first produced in September 1971, 3 months after construction was completed. Cumulative plots of measured drainage and percolation and the HELP model predictions for the period beginning in September 1971 are shown in Figure 56. Monthly plots are presented in Figure 57. These figures show very little measured leachate until the end of 1972. After that time, leachate drainage volumes somewhat exceed those predicted by HELP. Percolation volumes are negligible for both the field measurement and the model prediction. Over the 7-year period, leachate drainage accounted for 28.8 percent of the precipitation, while the HELP model predicted 24.6 percent. The model underpredicted the drainage by 4.2 percent of the precipitation or 14.6 percent of the measured drainage.

The field assessment of the test cell (16) at the end of the Boone County study indicated that secondary openings existed in the soil cover through which relatively rapid infiltration could have occurred. Therefore, a second HELP simulation was conducted using the highest of the three in-place hydraulic conductivity measurements of the soil cover, 7.0×10^{-5} cm/sec. These results, plotted in Figure 58, showed a predicted leachate drainage of 26.2 percent of the precipitation, yielding an error of -2.6 percent or -9.2 percent of the measured drainage. Both HELP simulations appeared to reasonably reproduce the measured results at the Boone County test cell.

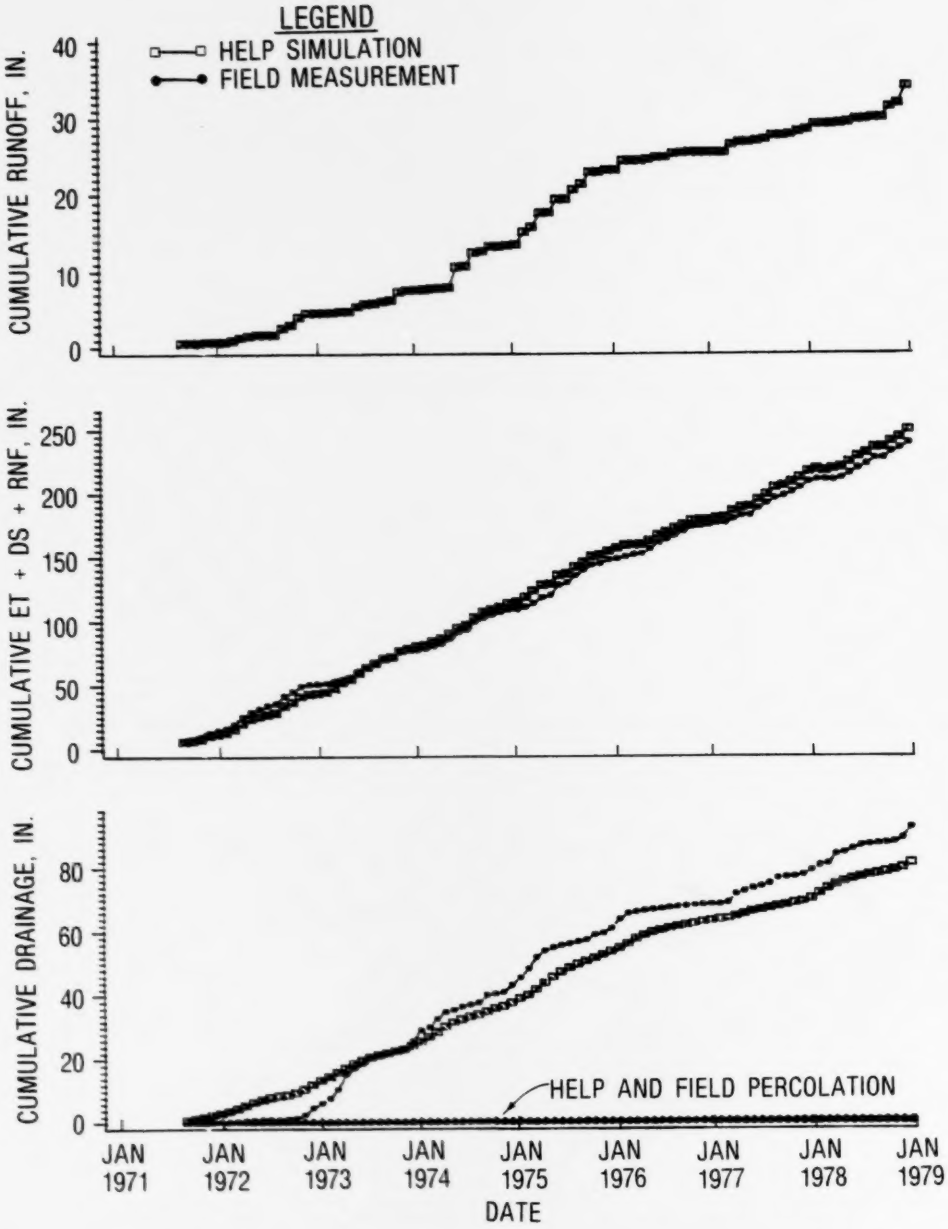


Figure 56. Field measurements for Boone County cell compared to HELP simulation; cumulative comparisons.

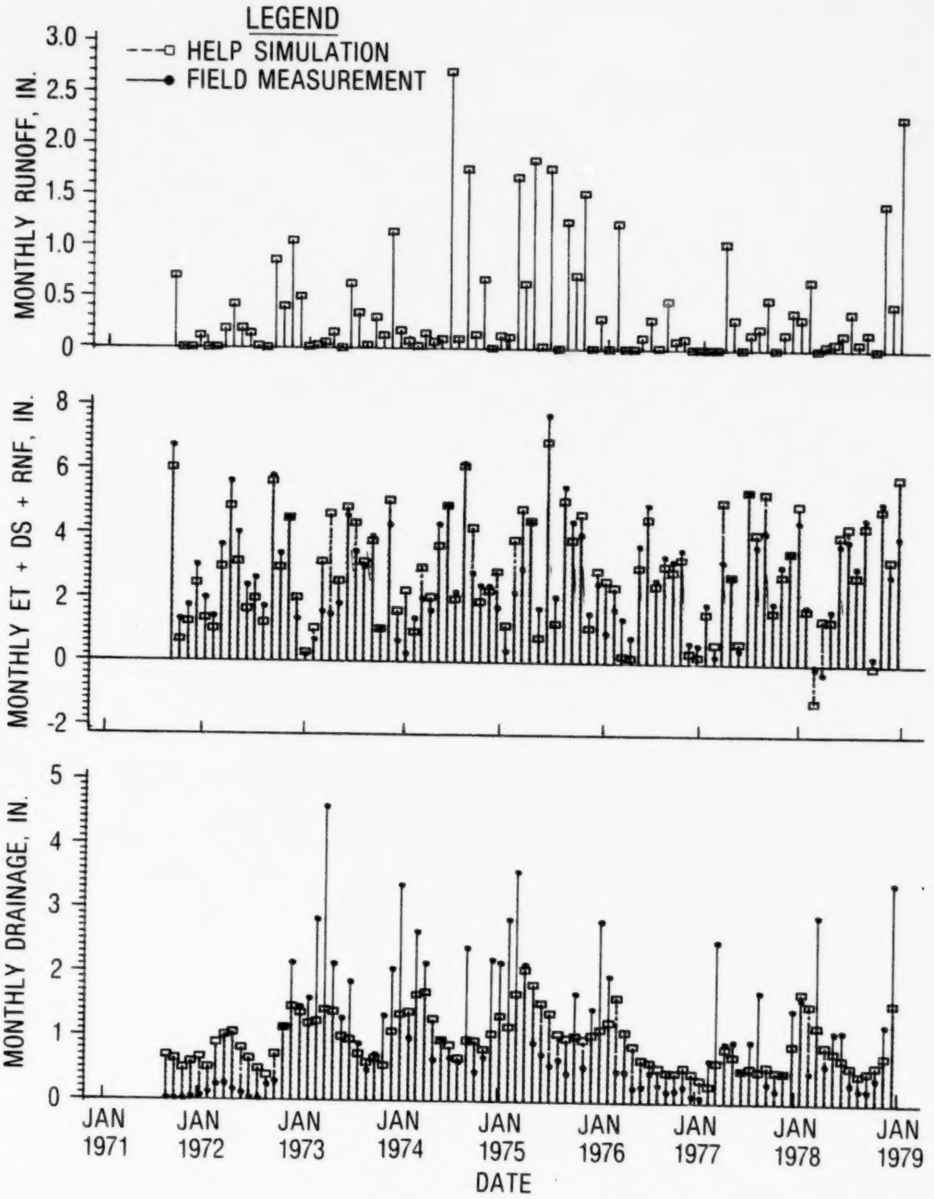


Figure 57. Field measurements for Boone County cell compared to HELP simulation; monthly comparisons.

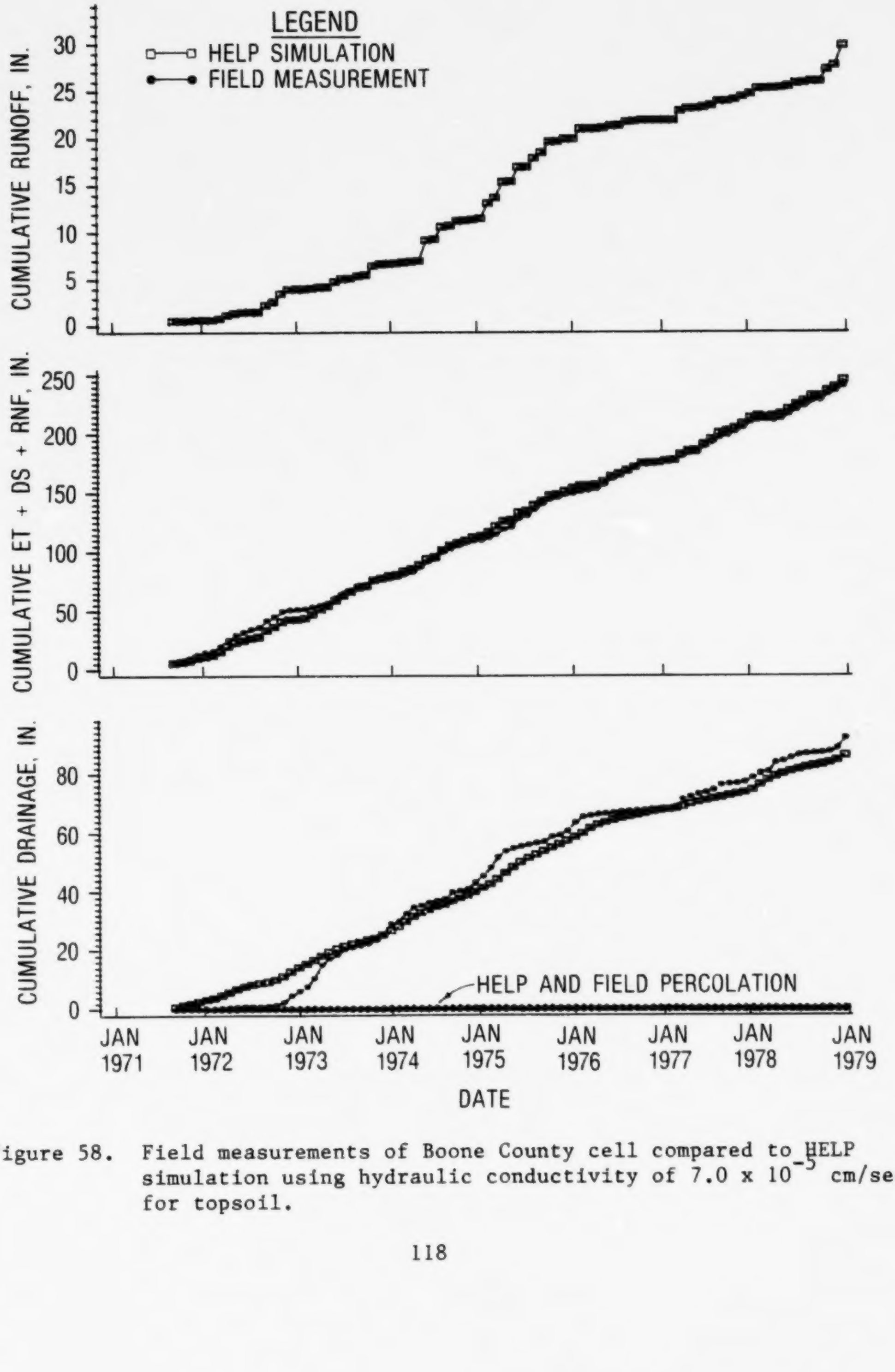


Figure 58. Field measurements of Boone County cell compared to HELP simulation using hydraulic conductivity of 7.0 x 10^{-5} cm/sec for topsoil.

SECTION 9

SIMULATION OF THREE COUNTY LANDFILLS IN WISCONSIN

The State of Wisconsin Bureau of Solid Waste Management (BSWM) has reported on the geologic setting, major design features, construction experience, and operational performance of four large landfills in Wisconsin (17). However, none of these landfills has yet been completely filled and capped, so that each data set collected thus far represents the conditions of a continuously expanding landfill. For example, at any given time, the cover could range from a 6-inch-thick blanket of sand to a final layer of clay and topsoil. This section presents HELP simulation results for a range of these conditions at three of the better documented sites--Brown County landfill, Eau Claire County landfill, and Marathon County landfill.

BROWN COUNTY LANDFILL

Site Description

The development of the Brown County landfill began in 1976 and is occurring in seven major sequences that will ultimately encompass an area of 58 acres. The landfill is located near Green Bay, WI, where the mean annual temperature is 44°F. The daily minimum temperature falls below freezing on 163 days per year. The mean annual precipitation is 27 inches, and the mean daily solar radiation is approximately 330 langleys.

A cross-sectional view of the landfill upon completion is shown in Figure 59. The base of the landfill consists of a 4-foot-thick compacted clay liner and a leachate collection system. Sequences 1 through 3 (approximately 17 acres) were designed with a 1-percent base slope, a leachate flow distance of 300 feet, and a 1-foot thick sand blanket on the base and sidewalls. The leachate flow distance was shortened to 100 feet for Sequence 4 (approximately 7 acres). The remaining three sequences have not been developed.

The waste initially consisted of municipal and commercial refuse. More recently, industrial waste consisting of flyash and water treatment plant sludge has been added. Daily cover is a 6-inch thickness of silty clay soil (USCS classification CL). During the period of leachate monitoring presented in this section, much of the landfill area was overlaid only with daily cover. Final cover consists of 2 feet of compacted clay and 6 inches of topsoil.

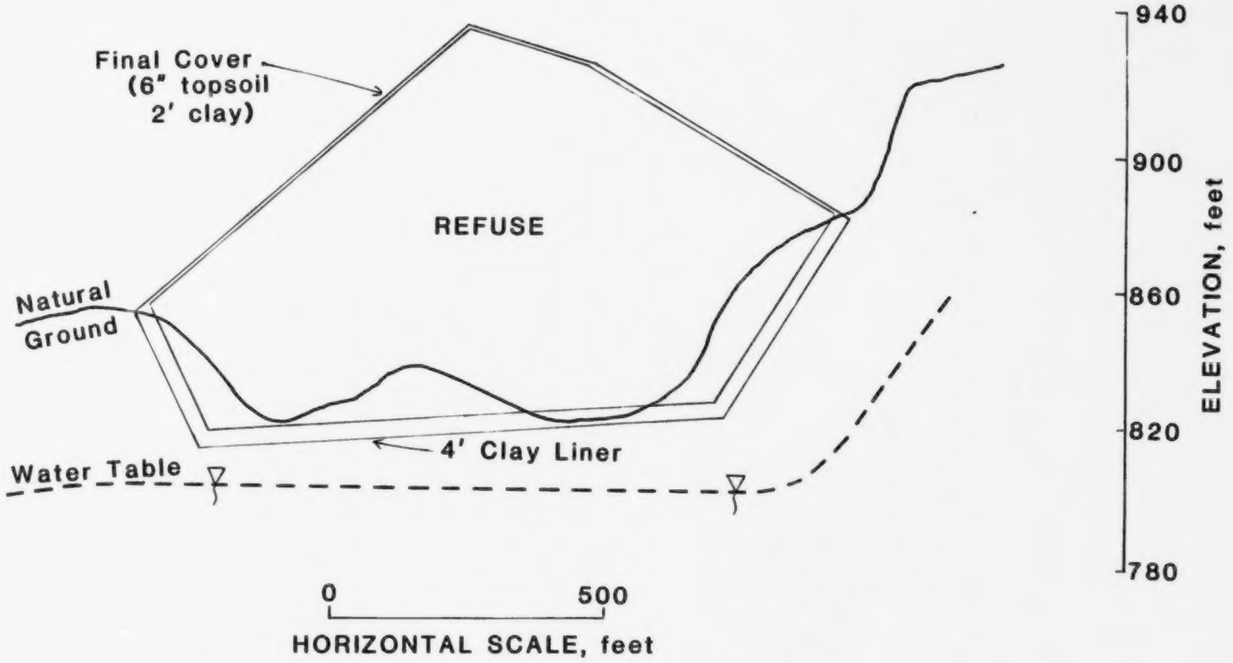

Final Cover
(6" topsoil
2' clay)
REFUSE
Natural
Ground
4' Clay Liner
Water Table
0
500
HORIZONTAL SCALE, feet
940
900
860
820
780
ELEVATION, feet

Figure 59. Cell dimensions for Brown County Landfill.

Selection of Model Input Values

Daily precipitation and mean monthly temperature measurements were taken from the NOAA weather station at Green Bay. Solar radiation values were the default values in the HELP model for Madison, WI.

Since the field data were collected during various stages of cover placement, two HELP simulations were conducted to encompass the range of cover conditions. First, the 6-inch daily cover was simulated using default soil texture 14 to represent the silty clay cover soil. Vegetation was assumed to be absent from this cover, and the evaporative depth was set to 4 inches to correspond to the recommendation in the HELP model for bare soil. Second, a 6-inch top soil layer (default soil texture 14) underlaid by a 24-inch compacted clay layer (default soil texture 18) was used to simulate the final cover conditions. Fair grass was assumed based on State of Wisconsin requirements for seeding the topsoil cover. An evaporative depth of 10 inches was used based on recommendations in the HELP model for fair grass. Since this evaporative depth penetrated into the top 4 inches of the compacted clay layer, this 4-inch section was treated as a vertical percolation layer while the remaining 20 inches was treated as a barrier soil layer. Runoff curve numbers were selected by the HELP model based on surface vegetation and the minimum infiltration rate of the topsoil.

An average depth of 75 feet was used for the waste layer. The waste characteristics were simulated using default soil texture 19. The 12-inch sand blanket below the waste layer was modeled as a lateral drainage layer using default soil texture 5. The 4-foot-thick clay liner was represented by default barrier soil texture 20 except for the hydraulic conductivity, which was taken to be 6.5×10^{-8} cm/sec, an average of in-place permeability tests. Table 16 summarizes all parameter values chosen for the simulations.

Results of Model Simulations

The site began accepting waste in August 1976, with routine leachate generation beginning in July 1977. The HELP simulations began in January 1977. The comparisons that follow represent the period from 1978 through 1983.

Figures 60 and 61 compare the field measurements to the results of the HELP model for daily cover. Figures 62 and 63 compare the field measurements to the results of the HELP model for the final cover. Table 17 summarizes differences between measured and computed results. Over the 6-year period, the daily cover simulation overestimated leachate drainage by 65 percent of the measured drainage, while the final cover simulation underestimated leachate drainage by 29 percent. Since the actual cover during the period was partial daily cover and partial final cover, the bracketing of the measured results by the two HELP simulations seems reasonable.

The difference between the two simulation results relates primarily to evapotranspiration. Although the runoff curve number was greater for the unvegetated daily cover, the small evaporative depth, relatively short

TABLE 16. INPUT DATA FOR SIMULATIONS OF BROWN COUNTY LANDFILL*

Parameter	Daily Cover Simulation	Final Cover Simulation
No. of layers	4	6
Layer 1		
Thickness (in.)	6	6
Layer type	1	1
Soil texture	14	14
Is layer compacted?	No	No
Layer 2		
Thickness (in.)	900	4
Layer type	4	1
Soil texture	19	18
Is layer compacted?	No	Yes
Layer 3		
Thickness (in.)	12	20
Layer type	2	3
Soil texture	5	18
Is layer compacted?	No	Yes
Layer 4		
Thickness (in.)	48	900
Layer type	3	4
Soil texture	20**	19
Layer 5		
Thickness (in.)		12
Layer type		2
Soil texture		5
Is layer compacted?		No
Layer 6		
Thickness (in.)		48
Layer type		3
Soil texture		20**
Type of vegetation	Bare	Fair
Evaporative depth (in.)	4	10
Slope of lateral drainage (%)	1	1
Drainage length (ft)	300	300

* Input data terminology defined in the HELP model documentation (1) and user's guide (2).

** Hydraulic conductivity = 6.5×10^{-8} cm/sec.

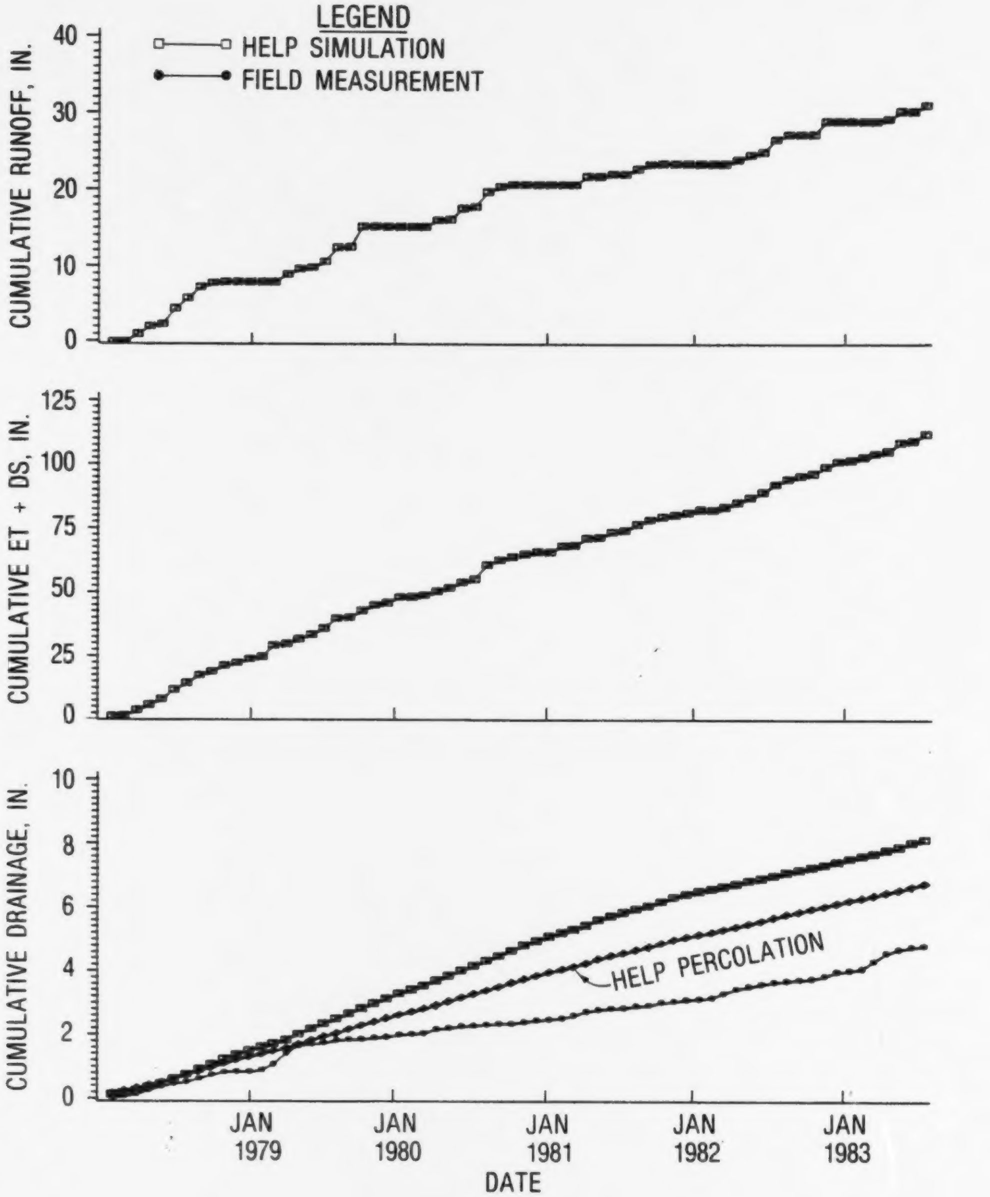


Figure 60. Field measurement of leachate drainage for Brown County landfill compared to HELP simulation for daily cover; cumulative comparison.

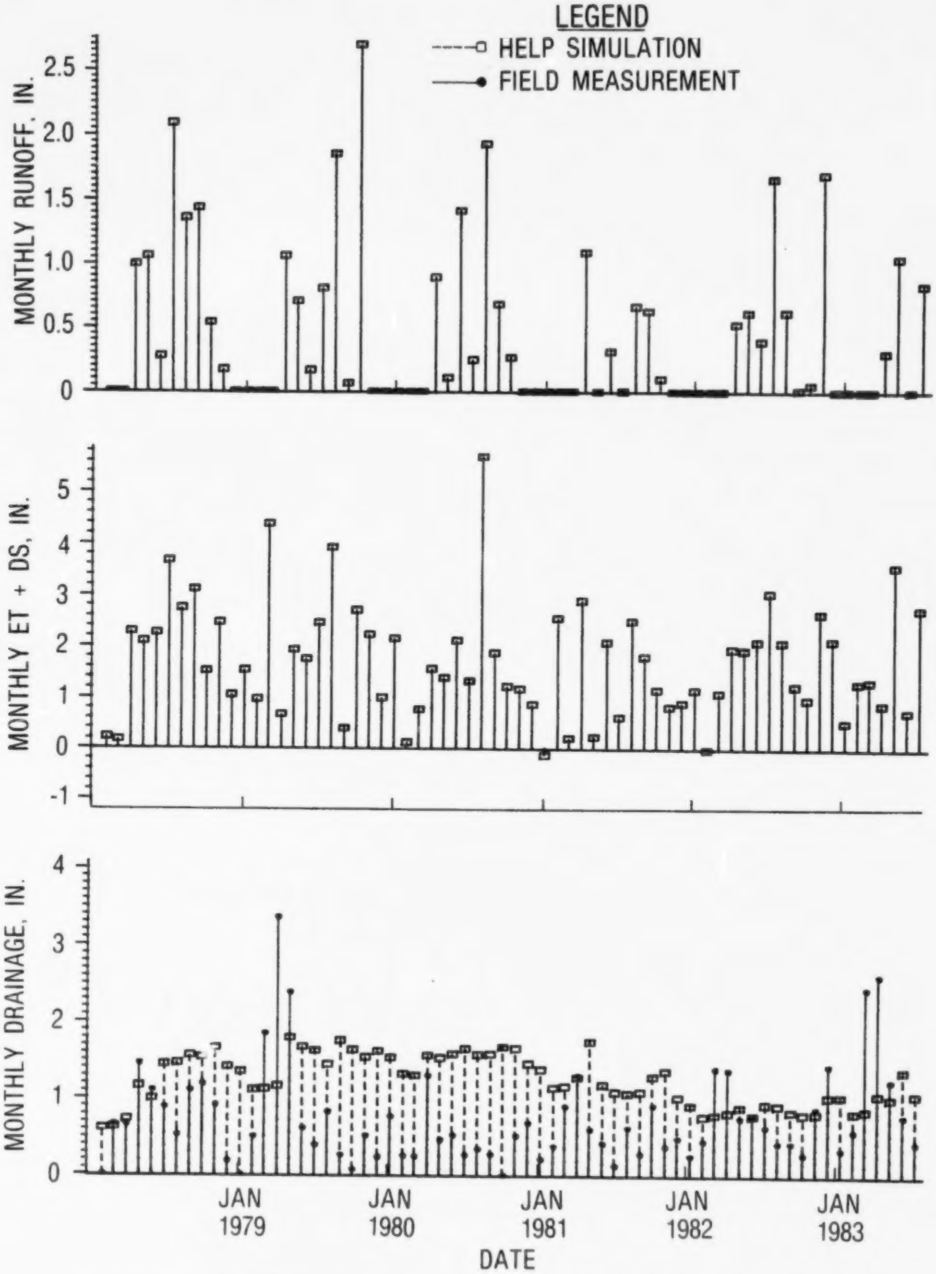


Figure 61. Field measurement of leachate drainage for Brown County landfill compared to HELP simulation for daily cover; monthly comparison.

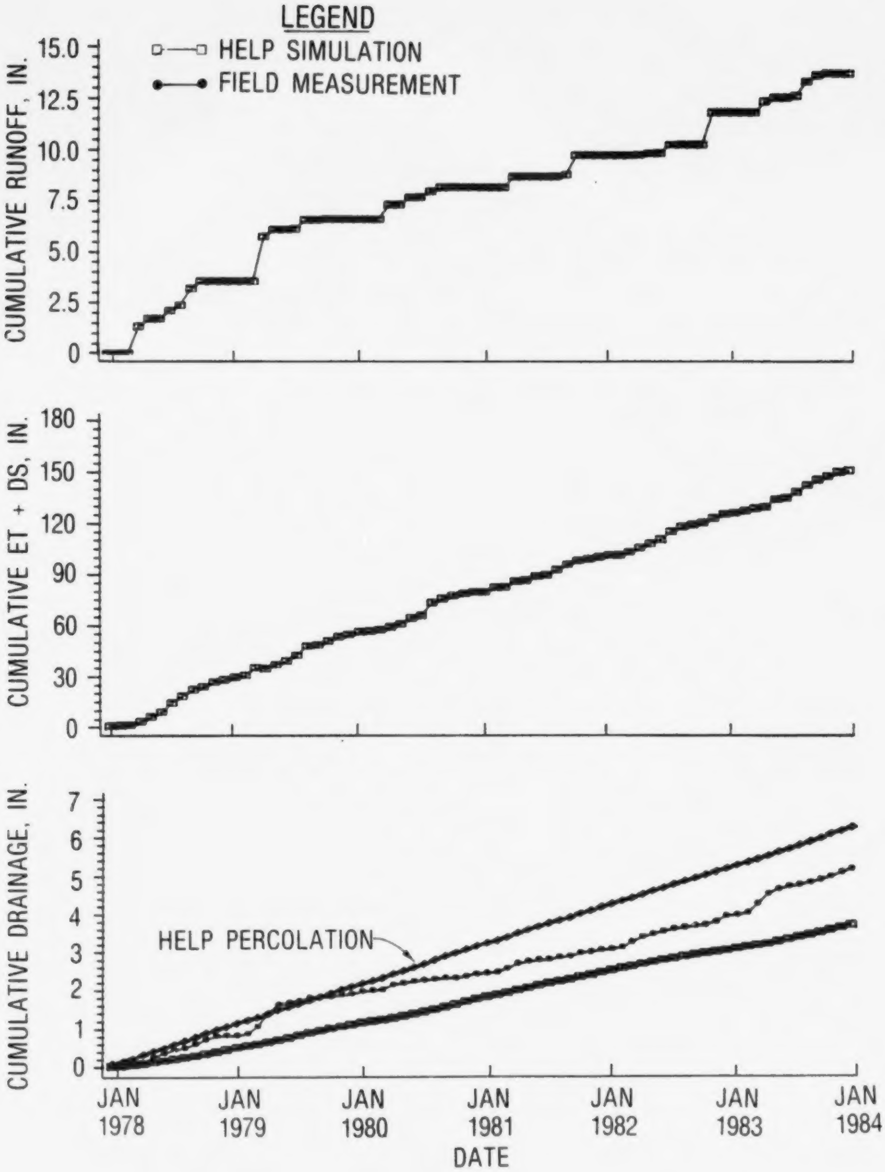


Figure 62. Field measurement of leachate drainage for Brown County landfill compared to HELP simulation for final cover; cumulative comparison.

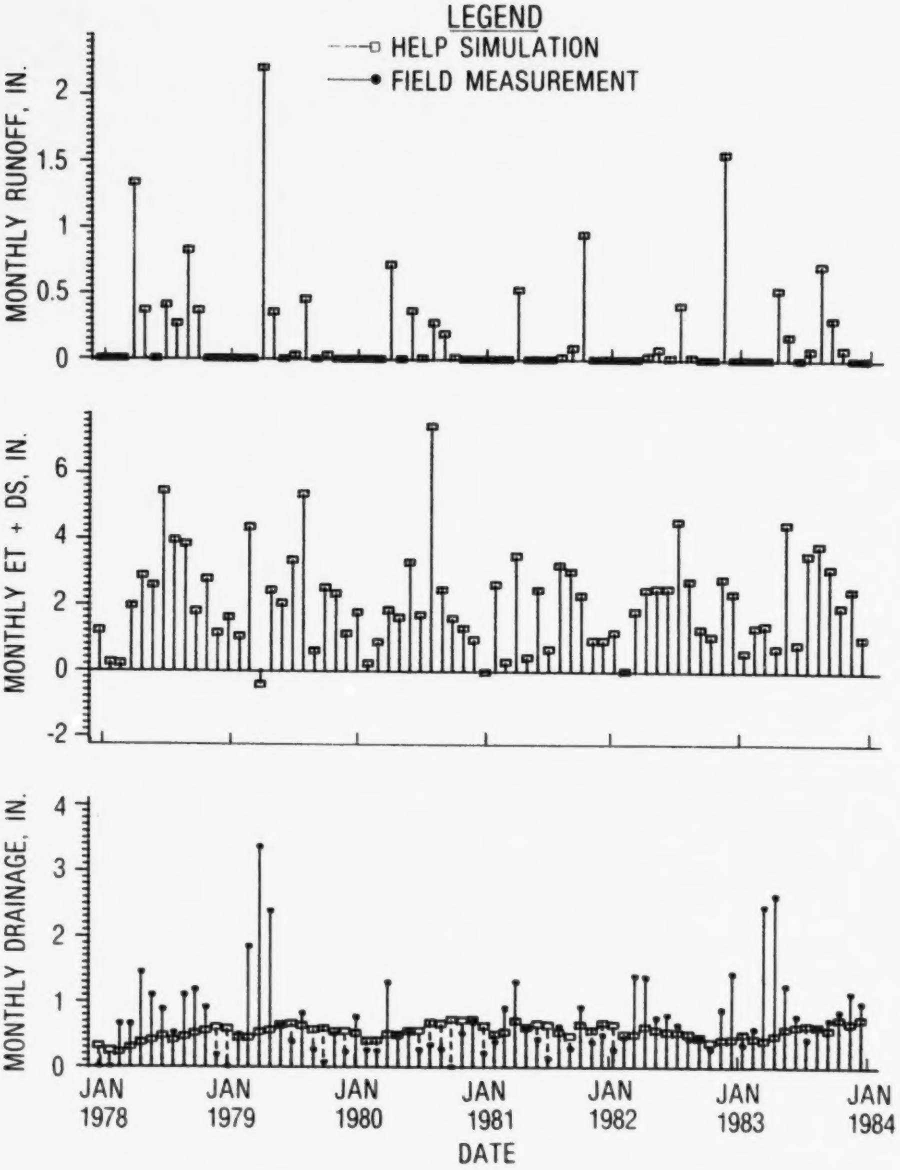


Figure 63. Field measurement of leachate drainage for Brown County landfill compared to HELP simulation for final cover; monthly comparison.

TABLE 17. DIFFERENCE BETWEEN CUMULATIVE HELP MODEL PREDICTIONS AND CUMULATIVE FIELD MEASUREMENTS FOR WISCONSIN COUNTY LANDFILLS

Simulation	Drainage Measured (% precip)	Predicted (% precip)	Error (% precip)	(%)
Brown County	3.1			
Daily cover		5.1	2.0	65
Final cover		2.2	-0.9	-29
Eau Claire County	7.7			
Daily sand cover		18.3	10.6	138
Interim sludge cover (Uncompacted clay)		0.3	-7.4	-96
Interim sludge cover (Clayey loam)		5.3	-2.4	-31
Final cover		17.5	9.8	127
Marathon County	6.9			
Daily cover		8.9	2.0	29
Final cover		4.6	-2.3	-33

travel time through the evaporative zone, and unrestricting hydraulic conductivity of the layer below the evaporative zone combined to allow large volumes of infiltration to pass through the cover. The final cover design with fair grass required a lower runoff curve number, but the greater evaporative depth, greater plant demand for moisture, and the greater residence time in the evaporative zone due to the restrictive clay barrier soil underlying the evaporative zone all combined to reduce volumes of infiltration through the cover.

A groundwater monitoring program at this site has detected small changes in quality immediately adjacent to and below the landfill. The percolation through the clay liner predicted by the HELP model during this period was approximately 8 inches, or 32 percent of the pore volume of the liner as estimated using the porosity for HELP default soil textures 20 and 21. With the limited information available, it is difficult to speculate whether this predicted percolation rate was sufficient to cause groundwater quality changes.

EAU CLAIRE COUNTY LANDFILL

Site Description

The Eau Claire County landfill opened in December 1978 in the vicinity of Eau Claire, WI. The ultimate size will be 24 acres. The data presented in this section cover the period of landfill expansion up to 14 acres.

The mean annual temperature is 43°F with 172 days per year experiencing a minimum temperature below freezing. The mean annual precipitation is 29 inches, and the mean daily solar radiation is approximately 330 langleys.

The base of the landfill consists of a 4-foot-thick compacted clay liner overlaid with a 1-foot-thick sand blanket and a leachate collection system. The liner slope is 1 percent, and the maximum leachate flow distance along the base is approximately 130 feet. The waste is primarily municipal and commercial refuse with minor amounts of industrial wastes.

Daily cover at this landfill is a 6-inch layer of sand. A 30-inch interim layer of papermill sludge covered a large percentage of the site during the period considered here. Final capping will include a 12-inch sand blanket over the sludge and then 6 inches of topsoil. The ultimate maximum fill thickness will be approximately 50 feet. A cross-sectional view of the landfill upon completion is shown in Figure 64.

Selection of Model Input Values

Daily precipitation and mean monthly temperature measurements were taken from the NOAA weather station at Eau Claire. Solar radiation values were the default values in the HELP model for Madison.

The modeling approach used here was similar to that used for the Brown County landfill simulations. Since the field data were collected during various stages of cover placement, four different HELP simulations were conducted to encompass the range of cover conditions. First, the 6-inch daily sand cover was simulated using default soil texture 3. Vegetation was assumed to be absent from this cover, so the evaporative depth was set to 4 inches to correspond to the recommendation in the HELP model for bare soil. Second, the 30-inch-thick interim sludge layer was simulated as an unvegetated cover. Two sets of default soil characteristics were used to describe this sludge cover. These were chosen based on comments by the State of Wisconsin BSWM (17) that field performance indicated that this sludge cover was more permeable than the typical clay cover. One simulation used uncompacted clay (soil texture 18) to describe the sludge cover and another used clayey loam (soil texture 14). Finally, the permanent capping was represented by a 6-inch layer of topsoil (soil texture 11) underlain by a 12-inch layer of sand (soil texture 3) over the 30-inch sludge layer (soil texture 14). Vegetation was assumed to be fair grass with an evaporative depth of 10 inches. Runoff curve numbers were selected by the HELP model based on surface vegetation and the minimum infiltration rate of the topsoil.

An average depth of 38 feet was used for the waste layer. The waste characteristics were simulated using default soil texture 19. The 12-inch sand blanket below the waste layer was modeled as a lateral drainage layer using default soil texture 5. The 4-foot-thick clay liner was represented by default barrier soil texture 20 except for the hydraulic conductivity, which was taken to be 1.4×10^{-7} cm/sec, an average of in-place permeability tests. Table 18 summarizes all parameter values chosen for the simulations.

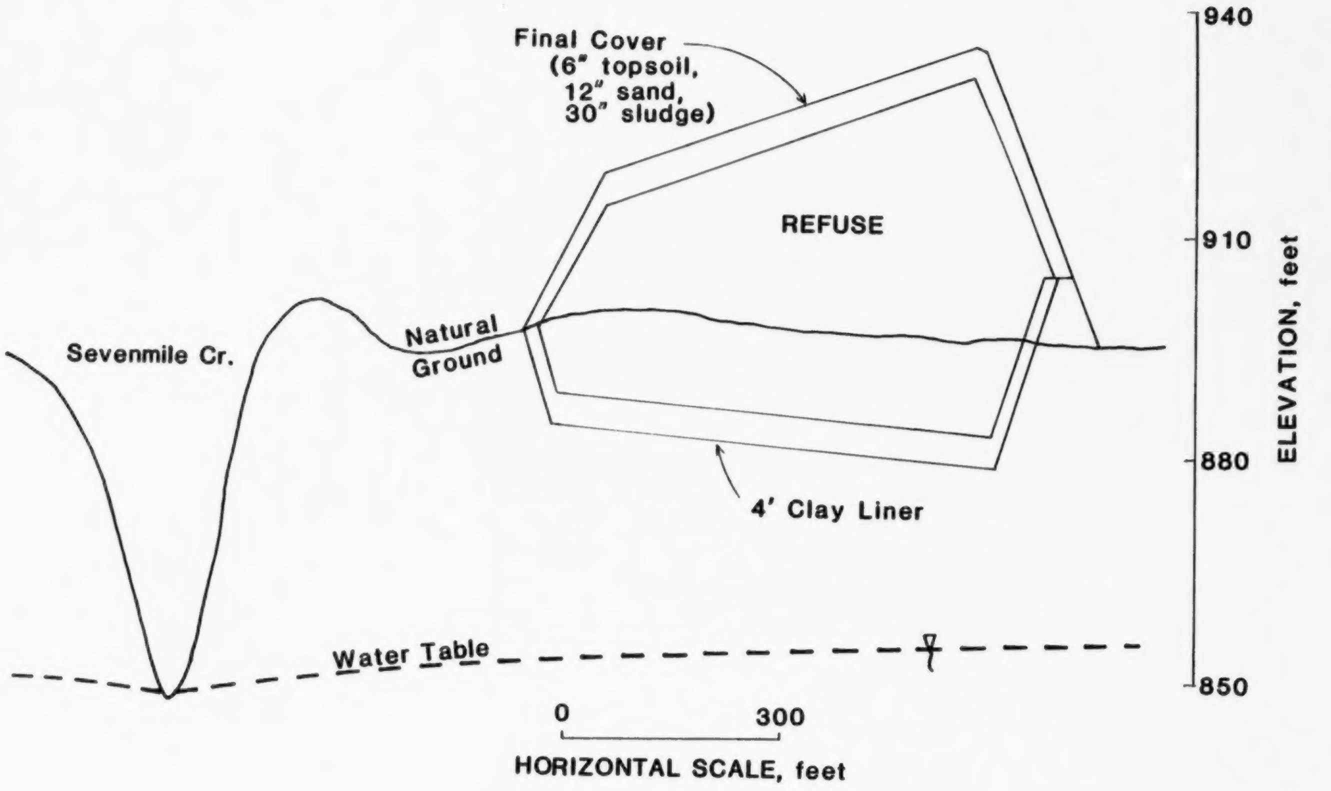

Final Cover
(6" topsoil,
12" sand,
30" sludge)
REFUSE
Sevenmile Cr.
Natural
Ground
4' Clay Liner
Water Table
0
300
HORIZONTAL SCALE, feet
940
910
880
850
ELEVATION, feet

Figure 64. Cell dimensions for Eau Claire County landfill.

TABLE 18. INPUT DATA FOR SIMULATION OF EAU CLAIRE COUNTY LANDFILL*

	Sand Cover	Sludge Cover as Uncompacted Clay	Sludge Cover as Clayey Loam Clay	Final Cover
No. of layers	4	4	4	6
Layer 1				
Thickness (in.)	6	30	30	6
Layer type	1	1	1	1
Soil texture	3	18	14	11
Is layer compacted?	No	No	No	No
Layer 2				
Thickness (in.)	450	450	450	12
Layer type	4	4	4	1
Soil texture	19	19	19	3
Is layer compacted?	No	No	No	No
Layer 3				
Thickness (in.)	12	12	12	30
Layer type	2	2	2	3
Soil texture	5	5	5	14
Is layer compacted?	No	No	No	No
Layer 4				
Thickness (in.)	48	48	48	450
Layer type	3	3	3	4
Soil texture	20**	20**	20**	19
Layer 5				
Thickness (in.)				12
Layer type				2
Soil texture				5
Is layer compacted?				No
Layer 6				
Thickness (in.)				48
Layer type				3
Soil texture				20**
Type of vegetation	Bare	Bare	Bare	Fair
Evaporative depth (in.)	4	4	4	10
Slope of lateral drainage (%)	1	1	1	1
Drainage length (ft)	130	130	130	130

* Input data terminology defined in the HELP model documentation (1) and user's guide (2).

** Hydraulic conductivity = 1.4×10^{-7} cm/sec.

Results of Model Simulations

The landfill opened in December 1978, and leachate generation began in the spring of 1979. The HELP simulations began in January 1979. The comparisons that follow represent the period from 1980 through 1984.

The results of the four simulations (monthly and cumulative) are presented in Figures 65 through 72. Table 17 summarizes differences between measured and computed results. The simulated leachate drainage compared to field measurements was 138 percent greater for the daily sand cover, 96 percent less for the uncompacted clay sludge cover, 31 percent less for the clayey loam sludge cover, and 127 percent greater for the final cover design. The large increase in leachate drainage for the daily sand cover is not surprising. The sand was modeled with a low runoff curve number, a large hydraulic conductivity, a small evaporative depth, and no surface vegetation--all of which contribute to high infiltration rates. The simulation of very small drainage volumes using uncompacted clay for the sludge cover tends to confirm that the sludge is more permeable than clay. The increase in leachate drainage for the final cover simulation must be qualified by the uncertainty of the sludge characteristics. However, the overall bracketing of the measured results by these simulations tends to confirm the general adequacy of the model.

Groundwater monitoring at the site has shown that there has been no measurable effect on groundwater quality due to the landfill. The percolation through the clay liner predicted by the HELP simulations ranged from 7 to 13 inches, or from 28 to 52 percent of the pore volume of the liner as estimated using the porosity for HELP default soil textures 20 and 21. These predictions appear to be reasonably consistent with the groundwater observations.

MARATHON COUNTY LANDFILL

Site Description

The landfill was opened in December 1980 in central Wisconsin near the city of Wausau. Approximately 27 acres have been licensed for waste disposal with 14 acres under development at the end of the data collection period presented in this section.

The mean annual temperature is 42°F with 170 days per year experiencing a minimum temperature below freezing. The mean annual precipitation is 31 inches, and the mean daily solar radiation is approximately 330 langleys.

The facility is designed with a 4-foot-thick compacted clay liner and a leachate collection system. The liner is sloped at 1 percent toward 8-inch-diameter perforated PVC pipes. The pipes are embedded in a 1-foot-deep trench oriented at approximately 45 degrees to the slope of the liner. The clay liner thickness increases to 5 feet in the vicinity of these trenches. The maximum leachate flow distance is about 250 feet in Phases 1 and 2 (9 acres total). Phase 3 (5 acres) was designed for a maximum flow distance of 100 feet. Following construction of the clay liner and installation of the

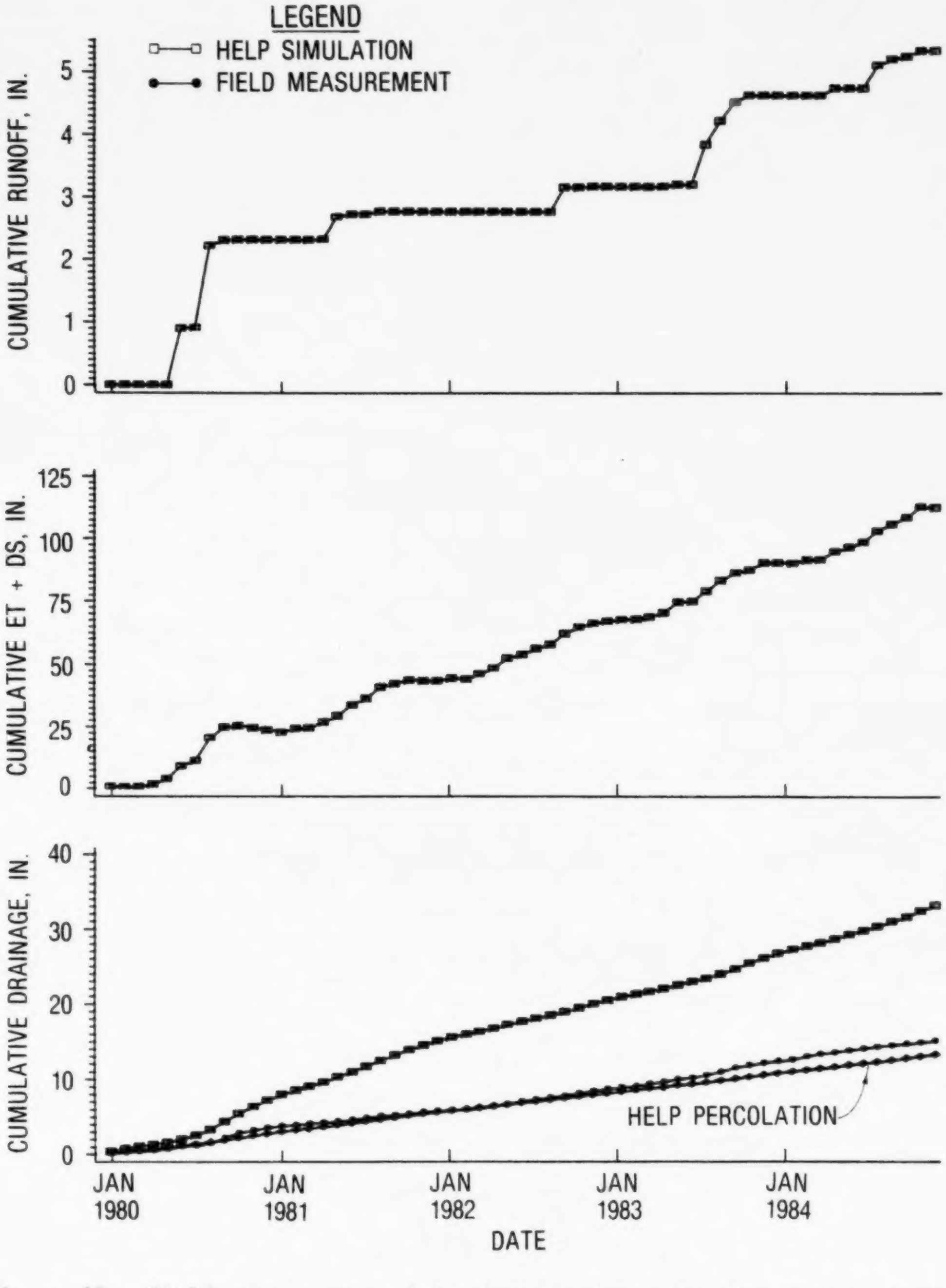


Figure 65. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for daily sand cover; cumulative comparison.

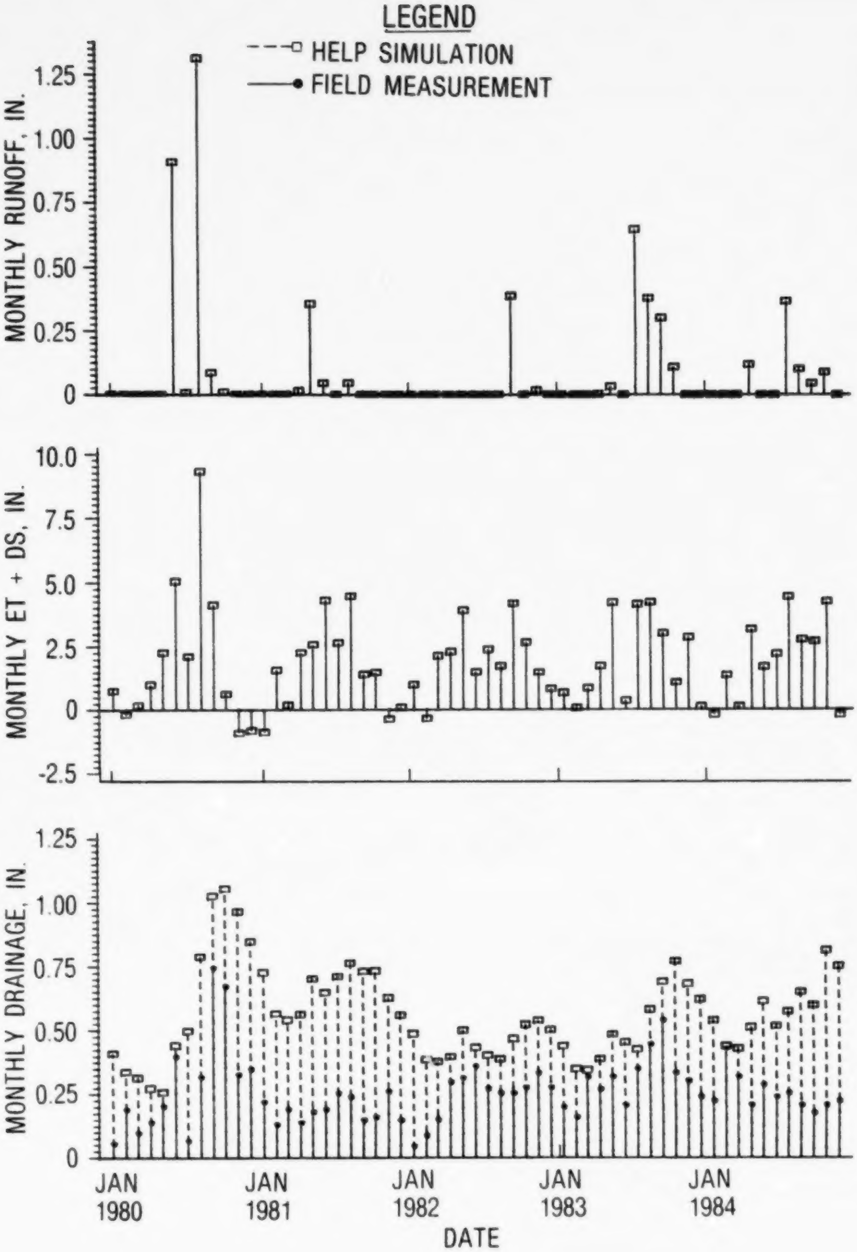


Figure 66. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for daily sand cover; monthly comparison.

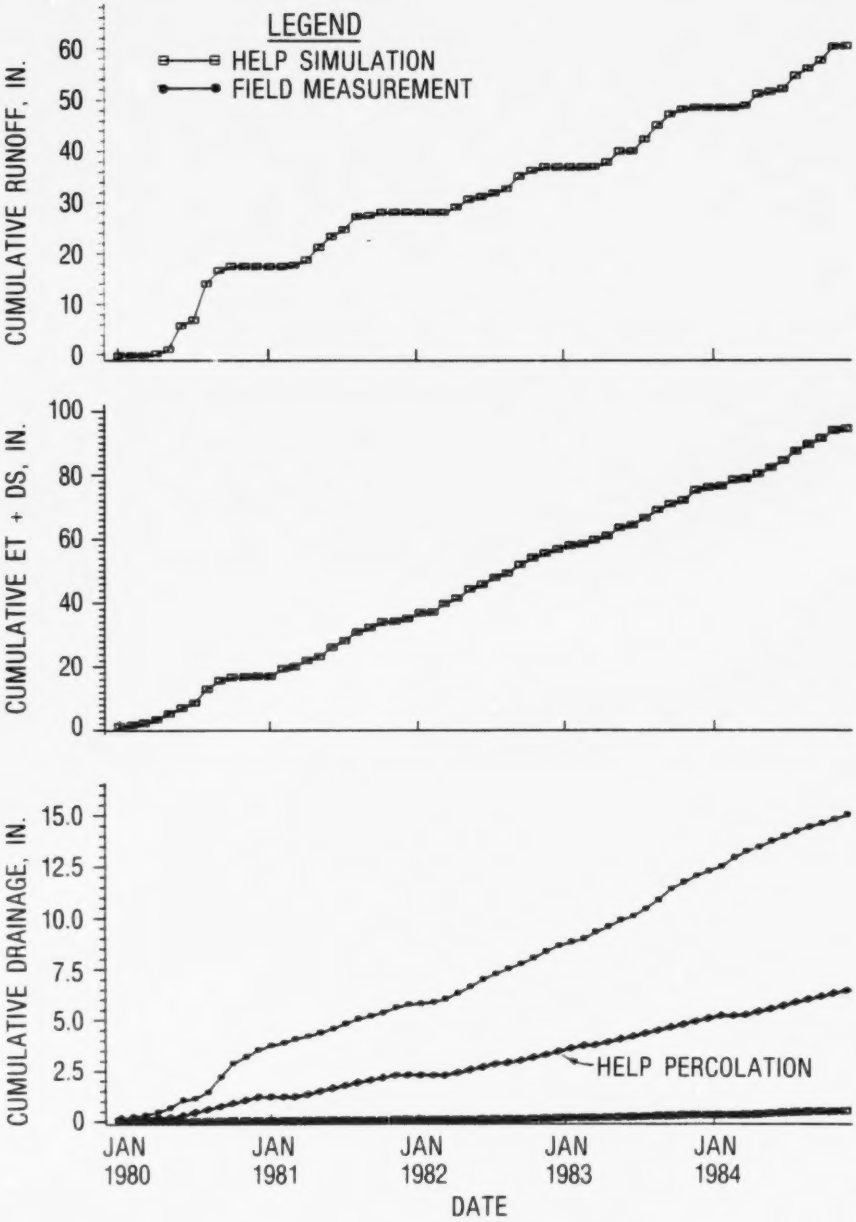


Figure 67. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for uncompacted clay sludge cover; cumulative comparison.

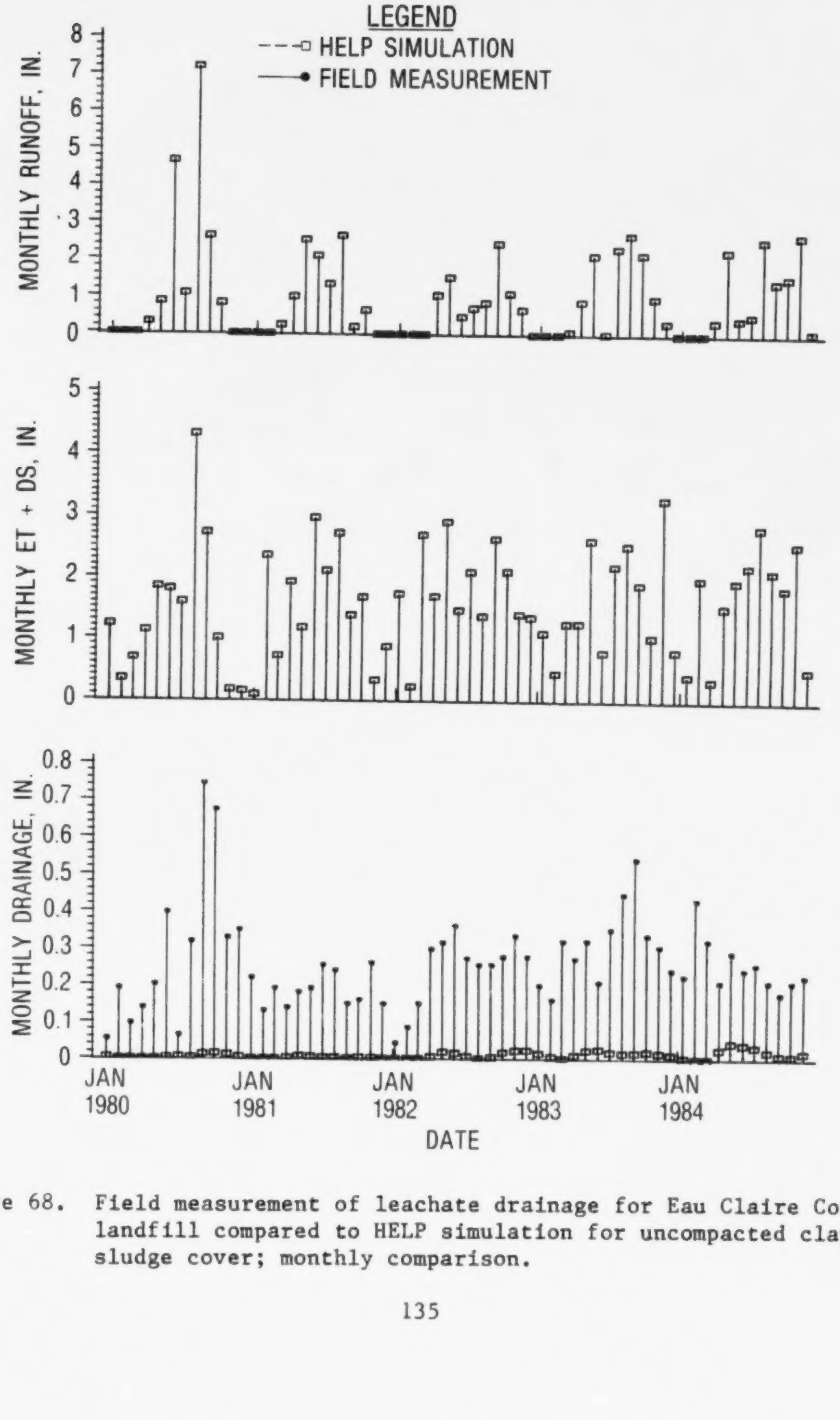


Figure 68. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for uncompacted clay sludge cover; monthly comparison.

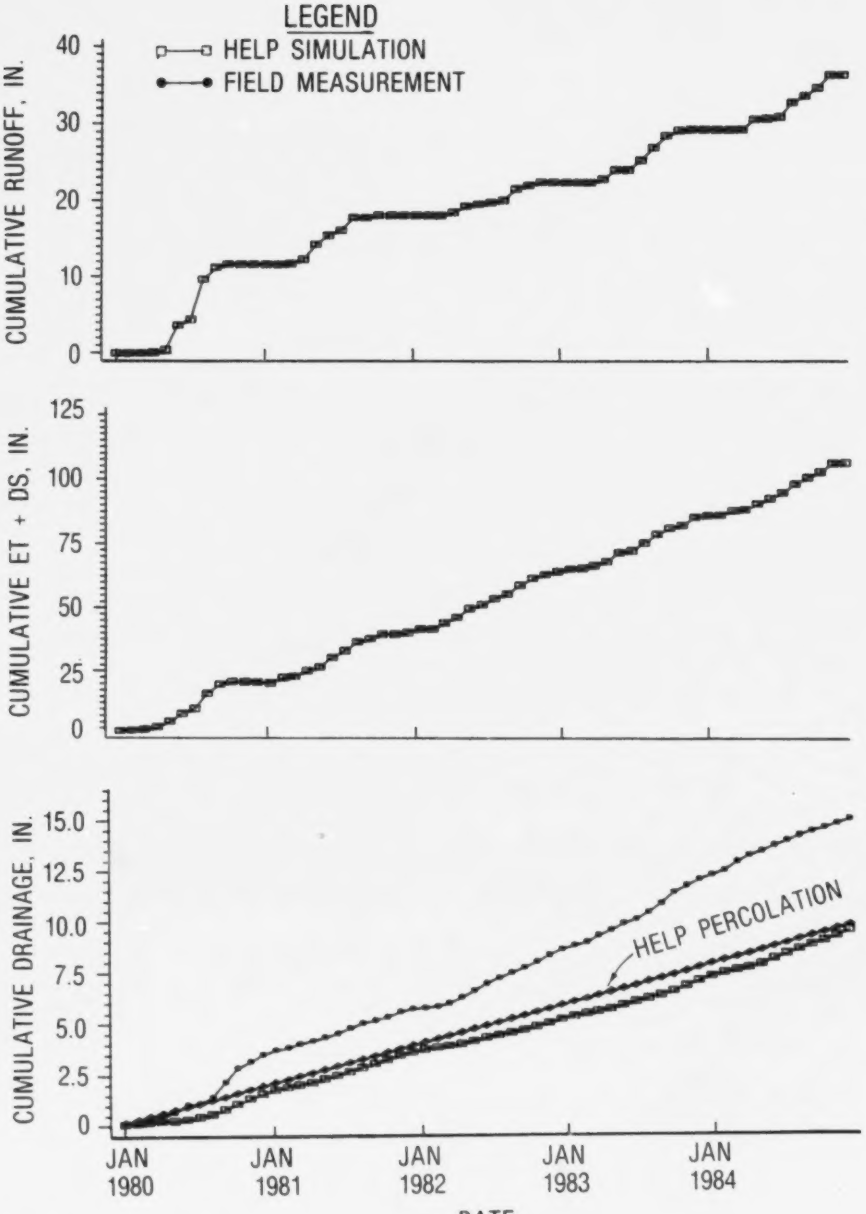


Figure 69. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for clayey loam sludge cover; cumulative comparison.

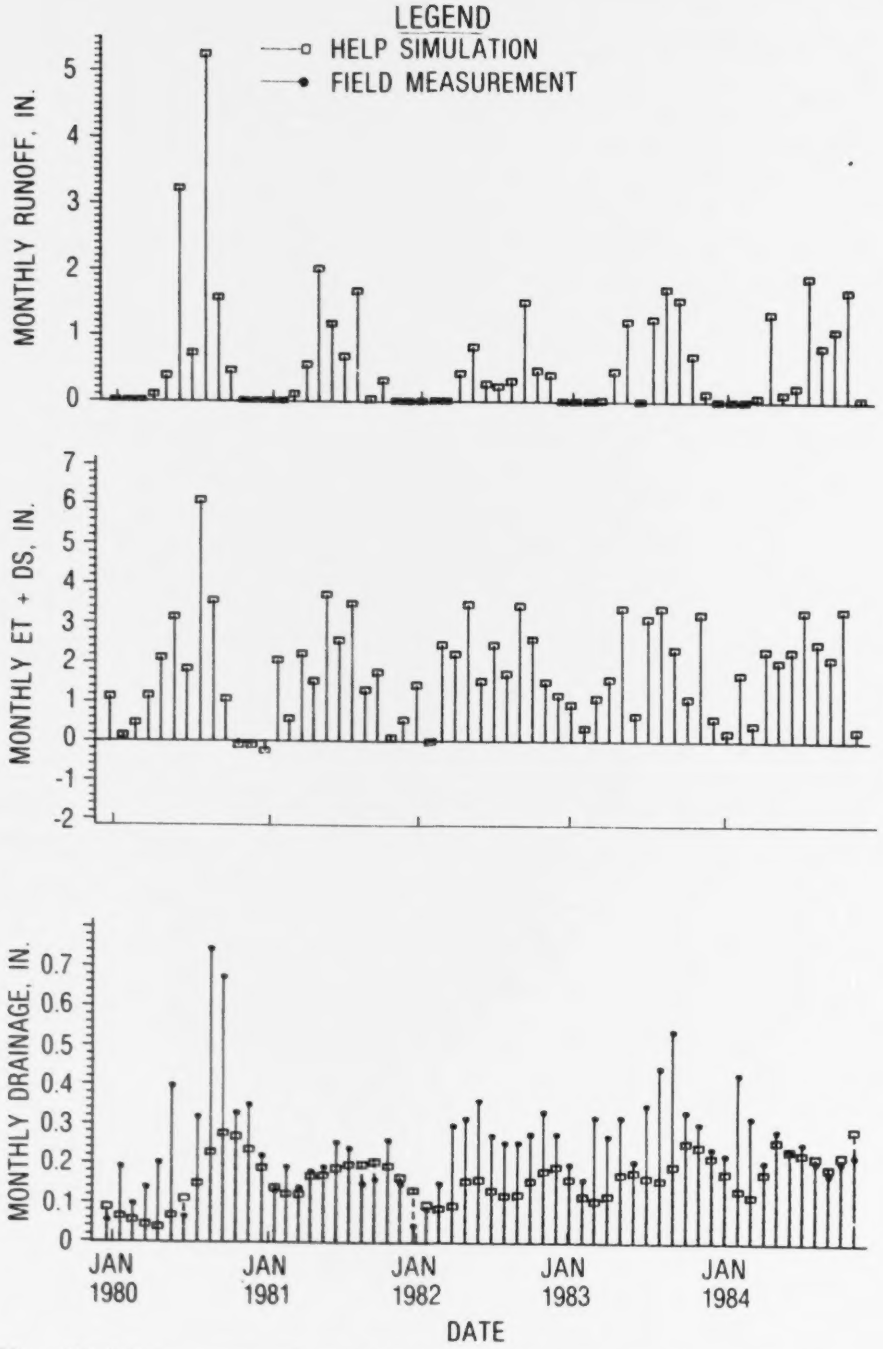


Figure 70. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for clayey loam sludge cover; monthly comparison.

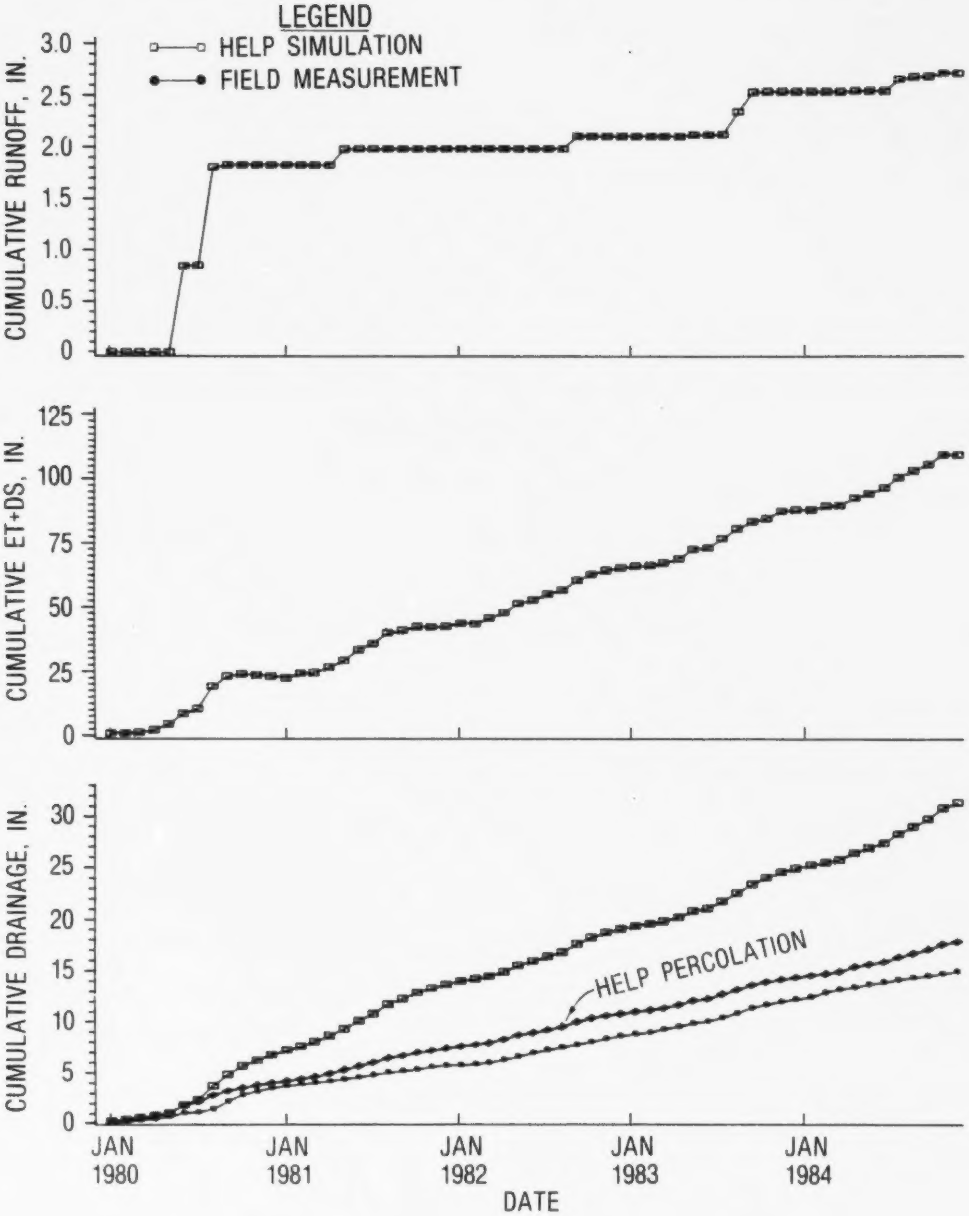


Figure 71. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for final cover; cumulative comparison.

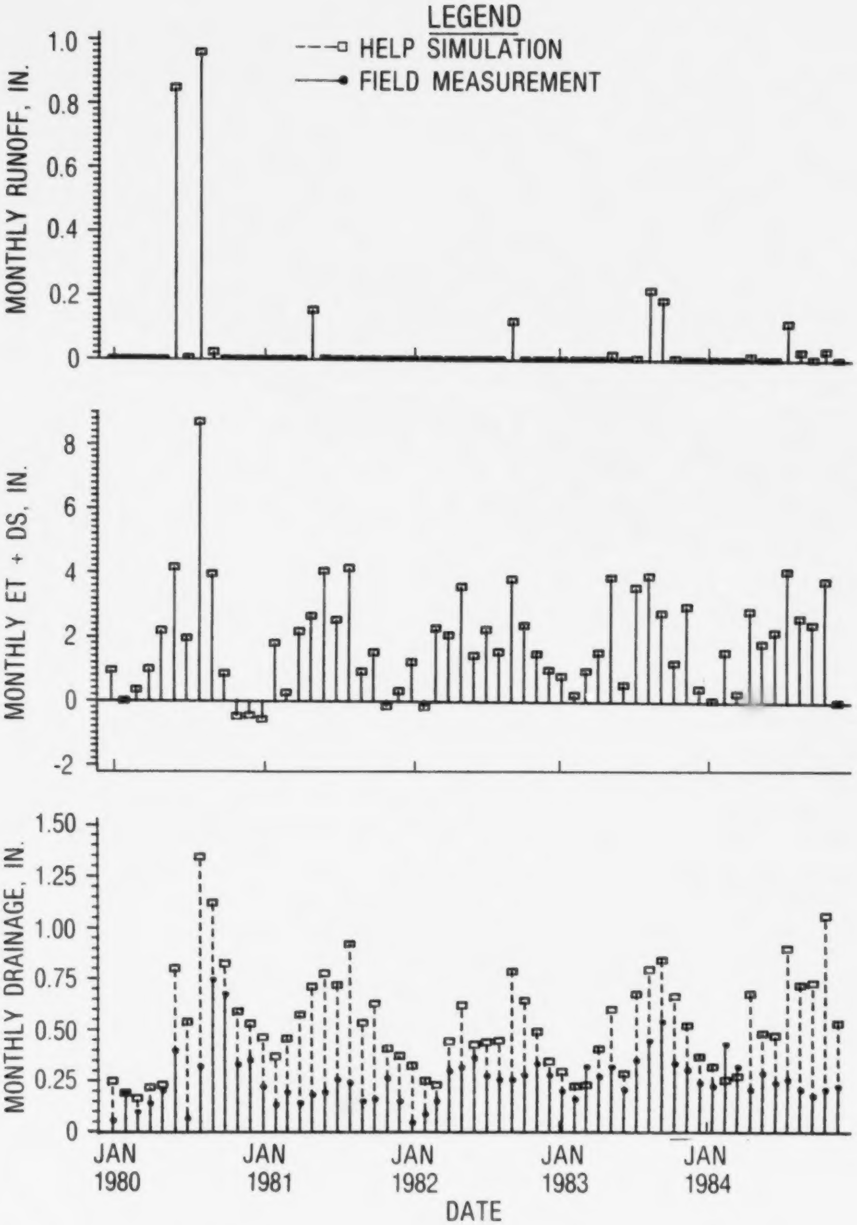


Figure 72. Field measurement of leachate drainage for Eau Claire County landfill compared to HELP simulation for final cover; monthly comparison.

collection pipe, a minimum 1-foot-thick silty sand drainage blanket was placed over the base and sidewalls.

The waste is 75 percent municipal refuse and 25 percent papermill sludge. The thickness of the waste layer ranges from 50 to 80 feet. The daily cover is 0.5 to 1.0 foot of sand. The final cover is 2 feet of clay covered by 6 inches of silty sand and 6 inches of topsoil.

Selection of Model Input Values

Daily precipitation and mean monthly temperature measurements were taken from the NOAA weather station at Wausau. Solar radiation values were the default values in the HELP model for Madison.

Two HELP simulations were performed--one for daily cover and the other for the final cover design. A 6-inch daily cover was simulated using the silty sand default soil texture 7 placed directly over the waste. Vegetation was assumed to be absent, so the evaporative depth was chosen to be 4 inches, corresponding to the recommended depth for bare soil in the HELP model. The final cover was simulated with a 6-inch topsoil layer whose characteristics were represented by the loam default soil texture 11. Below the topsoil, a 6-inch layer of silty sand was simulated using default soil 7. This was underlain by a 24-inch barrier layer of clay represented by the compacted characteristics of soil texture 18. Vegetation was assumed to be poor grass based on reports that only sparse vegetation was established on the topsoil during the period of record considered here. Runoff curve numbers were selected by the HELP model based on the assumed vegetative conditions and on the minimum infiltration rate of the topsoil.

An average depth of 60 feet was used for the waste layer which was simulated using default soil texture 19. The 12-inch sand blanket below the waste layer was modeled as a lateral drainage layer using default soil texture 7. The 4-foot-thick clay liner was represented by default soil texture 21 with a hydraulic conductivity of 3.0×10^{-9} cm/sec, an average of in-place permeability tests. Table 19 summarizes all parameter values chosen for the simulations.

Results of Model Simulations

The landfill began operation in December 1980, and leachate generation began approximately 5 months later. The HELP simulations began in January 1981. The comparisons that follow include 1981 through 1983 and are based on total annual leachate volume since monthly field data are not presently available.

Table 20 compares annual and cumulative leachate drainage volumes from field measurements and HELP predictions. Table 17 summarizes percent differences between the measured and computed results. For the initial year, 1981, field measurements significantly exceeded both HELP predictions. In the following 2 years, the predicted volumes increased so that the total cumulative measured volume fell between the daily cover and final cover

TABLE 19. INPUT DATA FOR SIMULATION OF MARATHON COUNTY LANDFILL*

Parameter	Daily Cover	Final Cover
No. of layers	4	6
Layer 1		
Thickness (in.)	6	6
Layer type	1	1
Soil texture	7	11
Is layer compacted?	No	No
Layer 2		
Thickness (in.)	720	6
Layer type	4	1
Soil texture	19	7
Is layer compacted?	No	No
Layer 3		
Thickness (in.)	12	24
Layer type	2	3
Soil texture	7	18
Is layer compacted?	No	Yes
Layer 4		
Thickness (in.)	48	720
Layer type	3	4
Soil texture	21**	19
Layer 5		
Thickness (in.)		12
Layer type		2
Soil texture		7
Is layer compacted?		No
Layer 6		
Thickness (in.)		48
Layer type		3
Soil texture		21**
Type of vegetation	Bare	Poor
Evaporative depth (in.)	4	8
Slope of lateral drainage (%)	1	1
Drainage length (ft)	250	250

* Input data terminology defined in the HELP model documentation (1) and user's guide (2).

** Hydraulic conductivity = 3.0×10^{-9} cm/sec.

TABLE 20. COMPARISON OF HELP SIMULATIONS TO FIELD MEASUREMENTS FOR MARATHON COUNTY LANDFILL

	Annual Leachate Drainage (in.)			Cumulative Leachate Drainage (in.)		
	1981	1982	1983	1981	1982	1983
HELP simulation using daily cover	0.8	2.9	5.7	0.8	3.7	9.4
HELP simulation using final cover	0.6	1.5	2.7	0.6	2.1	4.8
Field measurements	2.2	2.4	2.7	2.2	4.6	7.3

predictions for the overall 3-year period of record. In this case, it appears that the model and the field measurements are approaching equilibrium at different rates and that 3 years is an insufficient equilibration period. However, the field measurements appear to be converging to the final cover simulation. Overall, the daily cover simulation overestimated drainage by 29 percent of the measured value, while the final cover simulation underestimated drainage by 33 percent.

SECTION 10

SIMULATION OF CHEMICAL WASTE DISPOSAL FACILITY IN NIAGARA FALLS, NY

Since 1976, a chemical waste management company has filled and capped three landfill cells in Niagara Falls, NY. The surface areas of the cells range from 2 to 5 acres. Records of leachate pumpage have been kept from 1983 and indicate annual withdrawals ranging from 1 to 11 inches. An evaluation of the performance of the facility during 1984 was reported to the USEPA Region II by Recra Research, Inc. (18). Comparisons between field measurements and HELP simulations are presented below.

SITE DESCRIPTION

The site is located in Niagara Falls where the mean annual temperature is 48°F and where the daily minimum temperature falls below freezing on approximately 142 days per year. The mean annual precipitation is 35 inches, and the mean daily solar radiation is approximately 310 langleys.

The site is a former disposal area containing waste industrial slag ranging in depth from 7 to 50 feet. Beneath the slag is a layer of marsh silt ranging in thickness from a few inches to 5 feet. Below the silt is a 6-foot layer of lacustrine clay underlain by a 5-foot layer of glacial till. Excavation of the cells stopped at the lacustrine clay because of the high water table which required dewatering. A 10-foot-thick clay liner, compacted in 6-inch lifts, was placed at the bottom and along the side slopes of each cell. The hydraulic conductivity of this layer was specified to be 1×10^{-7} cm/sec or less. The bottom liner was sloped at 2 percent, and the sides were sloped at 2 horizontal to 1 vertical. Above this liner on both the cell bottom and side slopes was placed a "combination" liner consisting of 2 feet of compacted clay topped by a 30-mil synthetic liner and an additional 2 feet of compacted clay as shown in Figure 73. These clay layers were specified to have a maximum hydraulic conductivity of 1×10^{-7} cm/sec. The 30-mil synthetic liner was installed in Cell 1 only.

Stacked barrels containing chemical wastes are located on this combination liner. The depth of the waste layer is approximately 50 feet. Above the waste is a 3-foot layer of compacted clay, then two 6-mil synthetic liners, and finally a 1.5-foot layer of uncompacted clay. An underdrain is included in the uncompacted clay layer around the perimeter of the landfill. In Cell 1

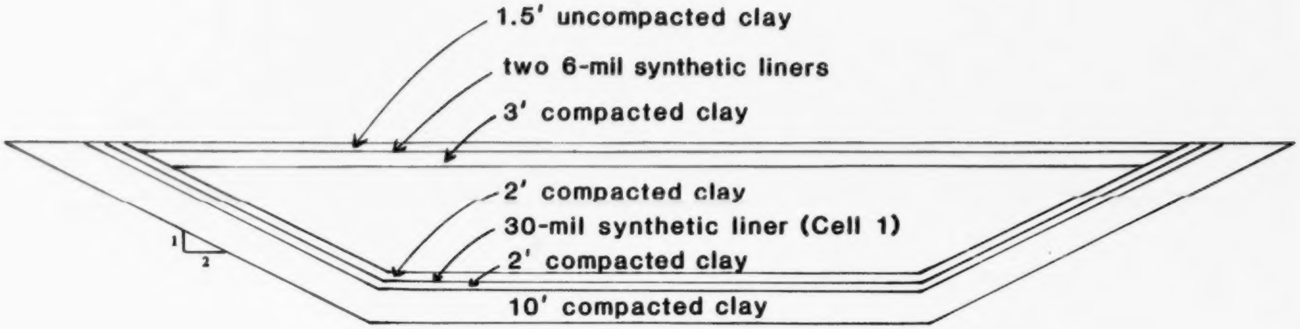

1.5' uncompacted clay
two 6-mil synthetic liners
3' compacted clay
2' compacted clay
30-mil synthetic liner (Cell 1)
2' compacted clay
10' compacted clay
1
2

Figure 73. Cell dimension for Niagara Falls cell.

only, the underdrain feeds into the leachate sump at the bottom of the cell. Surface areas are 1.93 acres for Cell 1, 2.50 acres for Cell 2, and 5.13 acres for Cell 3. Figure 73 shows a typical cross section through a cell.

The top clay layer was seeded with grass and is now kept mowed. Recent inspections indicate no signs of surface cracking, excessive subsidence and ponding, or excessive infiltration. Localized subsidence areas are repaired under an inspection program. The years of operation for Cells 1, 2, and 3 were 1976 to 1978, 1978 to 1981, and 1981 to 1983, respectively.

Cells 2 and 3 are divided into subcells by interior berms. Each subcell contains two standpipes into which leachate drains directly since no interior leachate collection pipes are contained within the cells. The leachate is pumped from the standpipes and metered on a regular basis. Since February 1984, level-activated pumps have been used to maintain accumulated leachate at lower levels within the cells. Cell 1 operates in a similar manner but it does not have interior berms. During the period January to June 1984, malfunctions occurred in the metering equipment, and the accuracy of the leachate volume measurements was questionable.

Recra Research, Inc. (18) presents measurements of groundwater levels outside the cells during 1984. These results show that groundwater levels remained above the base of the cells for significant periods of time.

SELECTION OF MODEL INPUT VALUES

Daily precipitation and mean monthly temperatures were taken from a NOAA weather station in Lockport, NY, approximately 15 miles from the landfill facility. Solar radiation values were the default values for Syracuse incorporated in the HELP model.

The clay soil cover was described using default soil texture 18. The top 18 inches was assumed to be uncompacted, while the underlying 36 inches was assumed to be compacted. The synthetic liner between these two soil layers was modeled by adjusting the hydraulic conductivity of the 36-inch layer based on an estimated leakage fraction through the synthetic liner as discussed later in this section. The drainage slope above this synthetic liner was set at 2 percent. The drainage length was 150 feet, an average distance from the center of the cover to the edge of the landfill.

The top 25-foot layer of waste was described using the default waste characteristics in the HELP model (soil texture 19). The bottom 25-foot layer was described using estimated characteristics for tightly packed stacked barrels with voids between barrels filled with a loosely packed coarse sand. This resulted in a composite porosity of 0.035 and field capacity of 0.017. The clay liner at the base was represented by soil texture 20, which has a hydraulic conductivity of 1×10^{-7} cm/sec.

The surface vegetation was assumed to be fair grass based on reports of seeding and mowing. The corresponding evaporative depth was chosen to be 10 inches as suggested by the HELP model for fair grass. A default runoff curve number of 89.6 was determined by the HELP model and was used in the simulations. A summary of all input values is presented in Table 21.

RESULTS OF MODEL SIMULATIONS

Leachate pumping records were made available for the period January 1983 to March 1985. Measured leachate volumes for Cell 1 include drainage from the perimeter underdrains in the soil cover. The HELP simulation curves for Cell 1 also include this additional component. Results for Cells 2 and 3 are shown together since their construction designs were essentially identical for the purposes of the HELP simulation.

The use of synthetic liners on the bottom, side slopes, and cover of Cell 1 theoretically should eliminate all inflow into the cell except for drainage from the perimeter underdrains, which is discharged directly into the leachate sump of Cell 1. However, HELP simulations indicated that this perimeter drainage accounted for less than 1 percent of the measured leachate volume. Other possible sources of inflow include surface runoff through direct connections to perimeter underdrains, leakage of infiltrated surface water through the clay and synthetic liners in the cover, and leakage of groundwater into the cell through the clay and synthetic liners on the bottom and side slopes. Of these possible sources, only leakage through the cover liners can be simulated in the HELP model; therefore, a leakage fraction in the cover was used in the Cell 1 simulations to account for additional inflow from these possible sources. It was assumed that leakage out of the cell through the bottom synthetic liner was negligible due to the high groundwater table.

Figures 74 and 75 show the simulation results for Cell 1 assuming a leakage fraction of 0.10 through the cover synthetic liner. The simulation reasonably matched measured volumes through about February 1984. After that time, the measured volumes significantly increased and deviated from the HELP prediction. The match prior to February 1984 with a 0.10 leakage fraction indicates either that significant inflows from other sources occurred after February 1984 or that the HELP simulation was underpredicting lateral drainage in the cover, or both.

The use of synthetic liners in the cover of Cells 2 and 3 theoretically should eliminate all surface water inflow into the cells since the perimeter underdrains are discharged offsite. Therefore, possible sources of the leachate volumes pumped from these two cells include leakage of infiltrated surface water through the clay and synthetic liners in the cover, and inflow of groundwater into the cell through the clay liner on the bottom and side slopes. As described for Cell 1, a leakage fraction through the cover synthetic liner was used in the Cell 2 and 3 simulations to account for additional inflow from these possible sources. As for Cell 1, it was assumed that leachate percolation out of the cell through the bottom clay liner was negligible due to the high water table.

TABLE 21. INPUT DATA FOR NIAGARA FALLS LANDFILL SIMULATION*

Parameter	Value
No. of Layers	6
Layer 1	
Thickness (in.)	12
Layer type	1
Soil texture	18
Is layer compacted?	No
Layer 2	
Thickness (in.)	6
Layer type	2
Soil texture	18
Is layer compacted?	No
Layer 3	
Thickness (in.)	36
Layer type	3
Soil texture	18
Is layer compacted?	Yes
Layer 4	
Thickness (in.)	300
Layer type	4
Soil texture	19
Layer 5	
Thickness (in.)	300
Layer type	2
Soil texture	**
Is layer compacted?	No
Layer 6	
Thickness (in.)	168
Layer type	3
Soil texture	20
Linear leakage fraction	0.10
Type of vegetation	Fair
Evaporative depth (in.)	10
Surface area (sq ft)	84,000
Slope of lateral drainage (%)	2
Drainage length (ft)	150

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* Input data terminology defined in the HELP model documentation (1) and user's guide (2).

** Porosity = 0.035; field capacity = 0.017; hydraulic conductivity = 10.0 in./hr or 0.007 cm/sec.

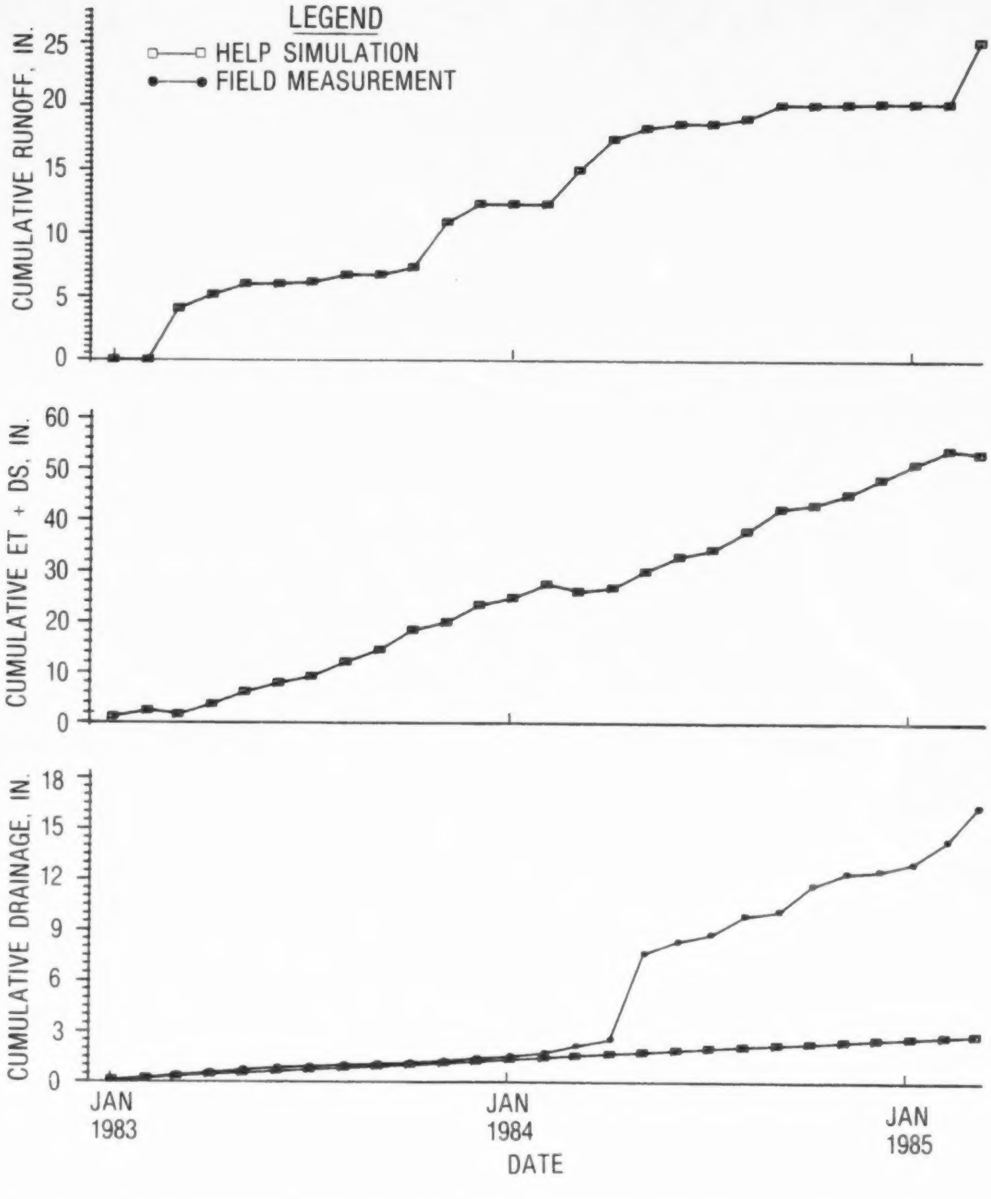

Figure 74. Field measurement of leachate drainage for Niagara Falls Cell 1 compared to HELP simulation; cumulative comparison.

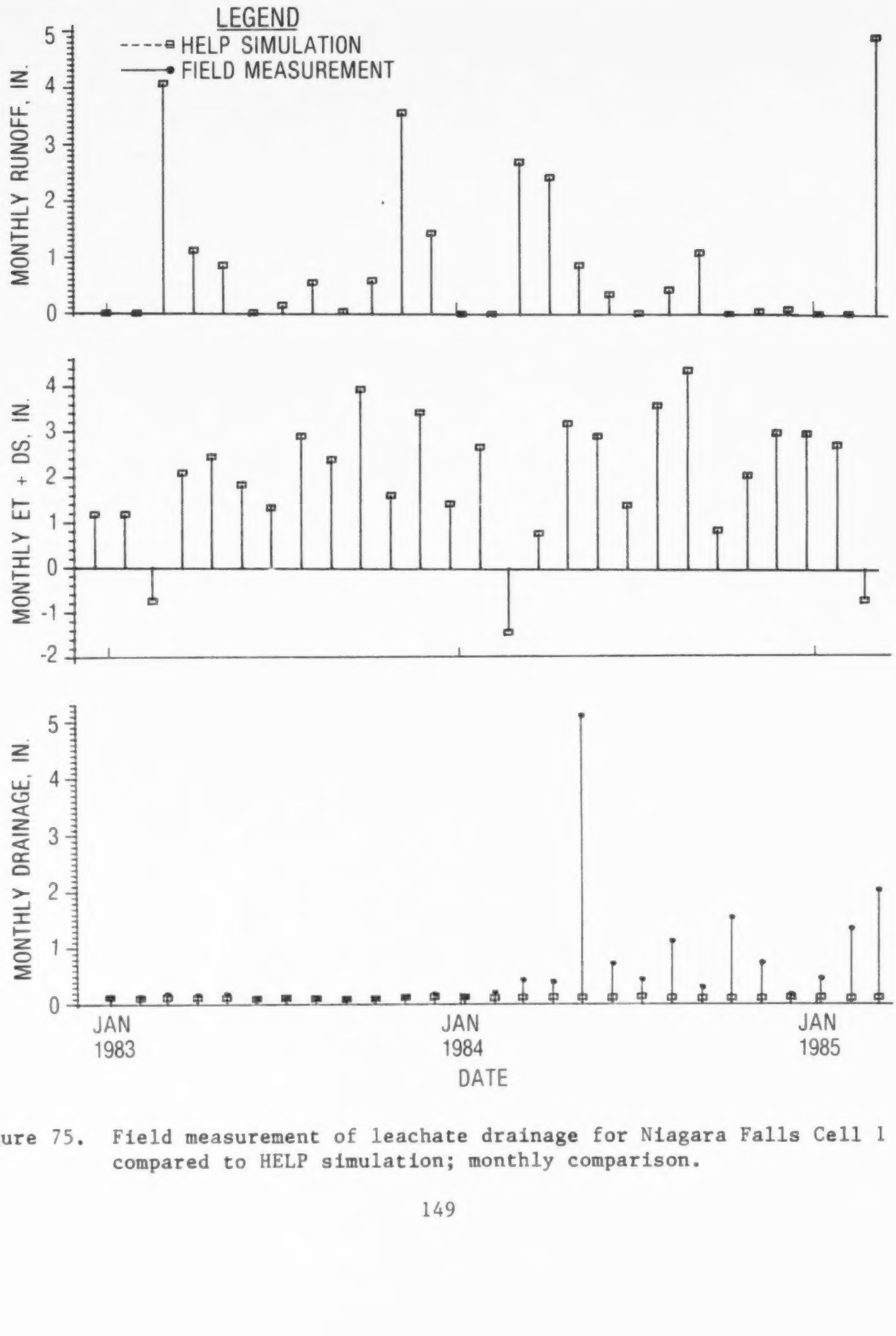

Figure 75. Field measurement of leachate drainage for Niagara Falls Cell 1 compared to HELP simulation; monthly comparison.

Figures 76 through 78 show the simulation results for Cells 2 and 3 assuming a leakage fraction of 0.10 through the cover synthetic liner. In this case, the simulation reasonably matched measured volumes in Cell 2 through about February 1984 but underestimated measured volumes in Cell 3 throughout the period of record.

The period of metering equipment malfunction (January to June 1984) fell within the period of greatly increased measured volumes of leachate (after February 1984). However, the large measured volumes were sustained beyond the period of equipment malfunction, implying that the equipment was not entirely responsible for the reporting of increased volumes.

The date when the measured leachate volumes began to significantly increase was the same in all cells and corresponded to the date when level-actuated pumps were first used to discharge leachate from the cells. This fact, combined with the knowledge of high groundwater levels, strongly suggests that the lower ponding depths maintained by the new pumps increased the hydraulic gradient across the landfill liner, increasing the rate of groundwater inflow into the cells. If this was the case, the 0.10 leakage fraction which matched measured results prior to February 1984 was probably due more to groundwater inflow than a grossly underpredicted lateral drainage rate in the cover or a large leakage fraction through the cover synthetic liner.

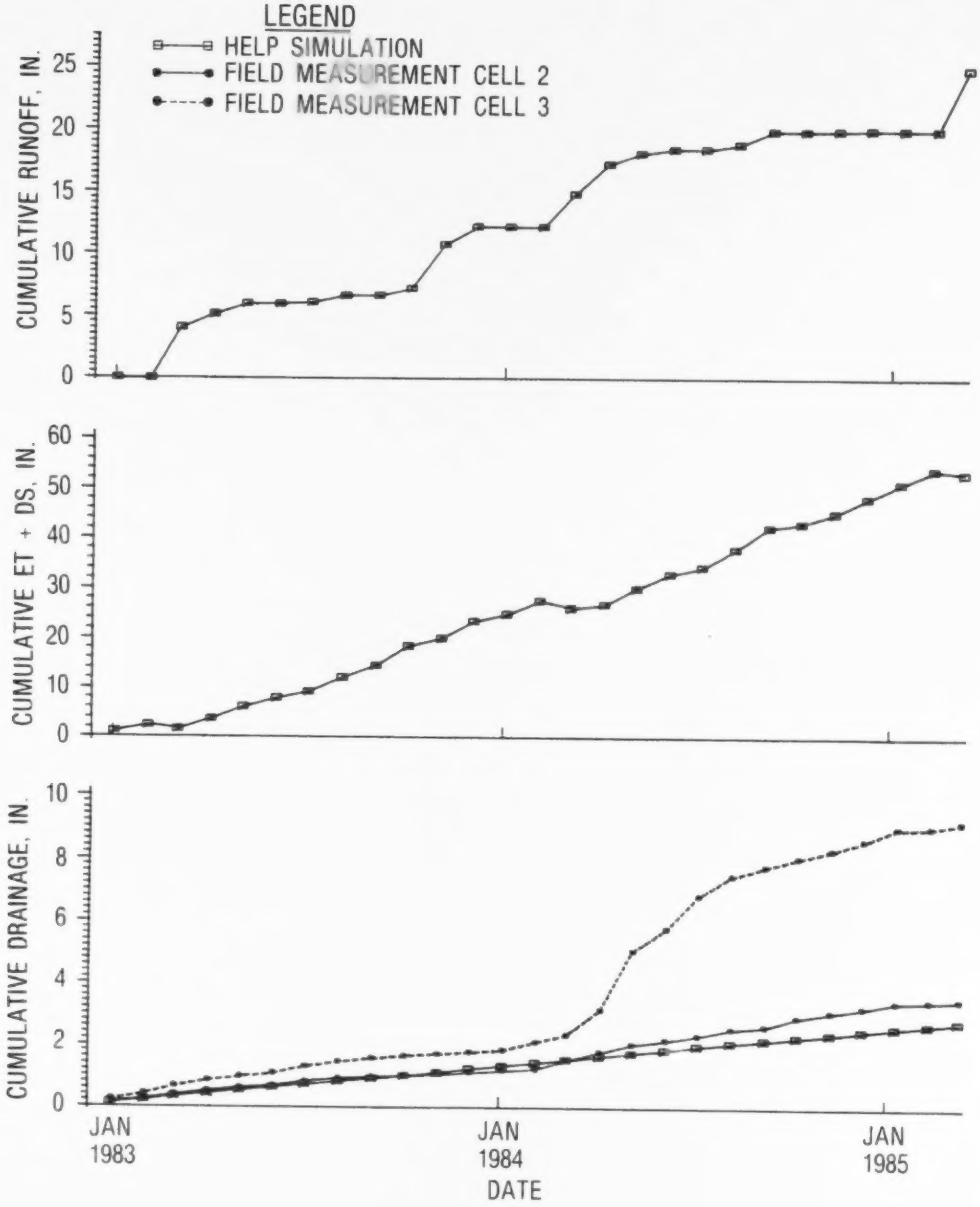

Figure 76. Field measurements of leachate drainage for Niagara Falls Cells 2 and 3 compared to HELP simulation; cumulative comparisons.

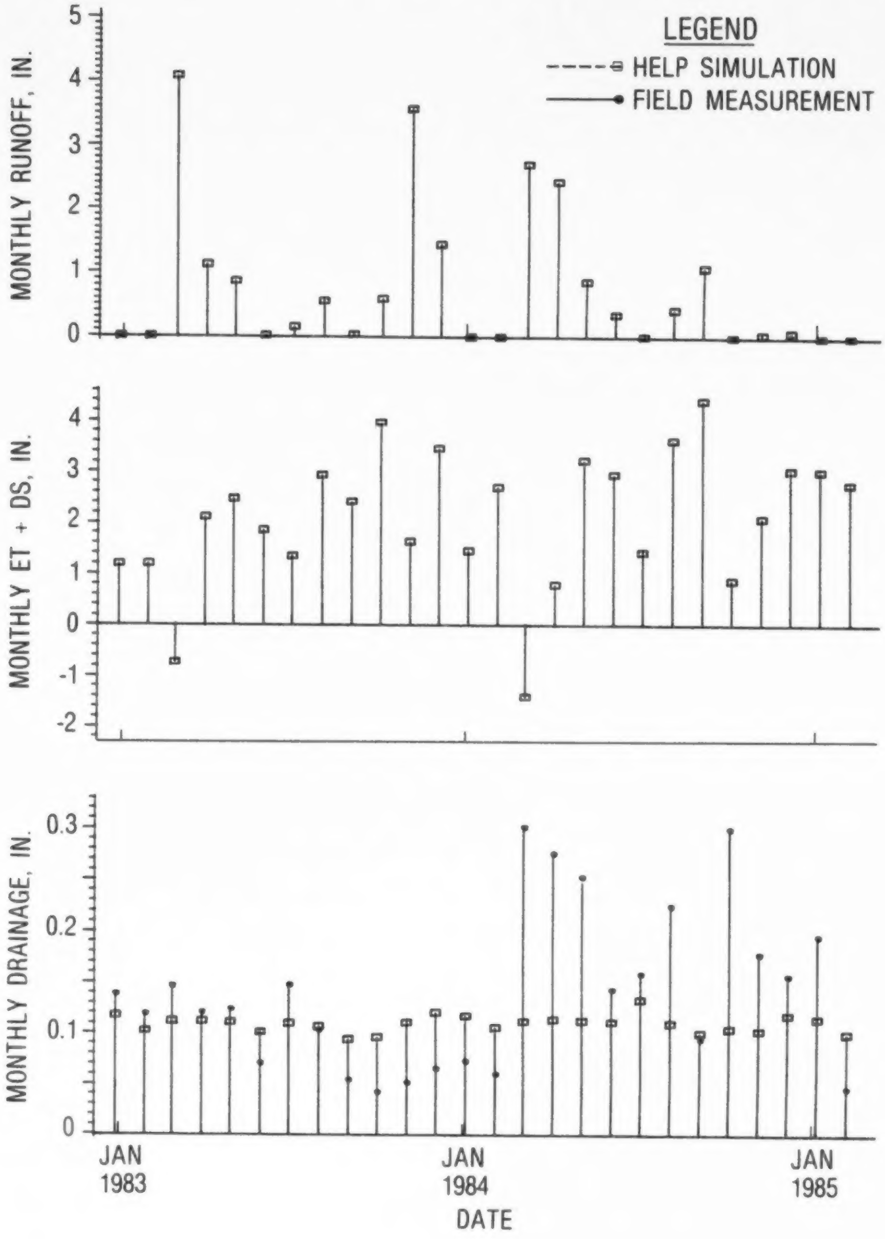

Figure 77. Field measurement of leachate drainage for Niagara Falls Cell 2 compared to HELP simulation; monthly comparisons.

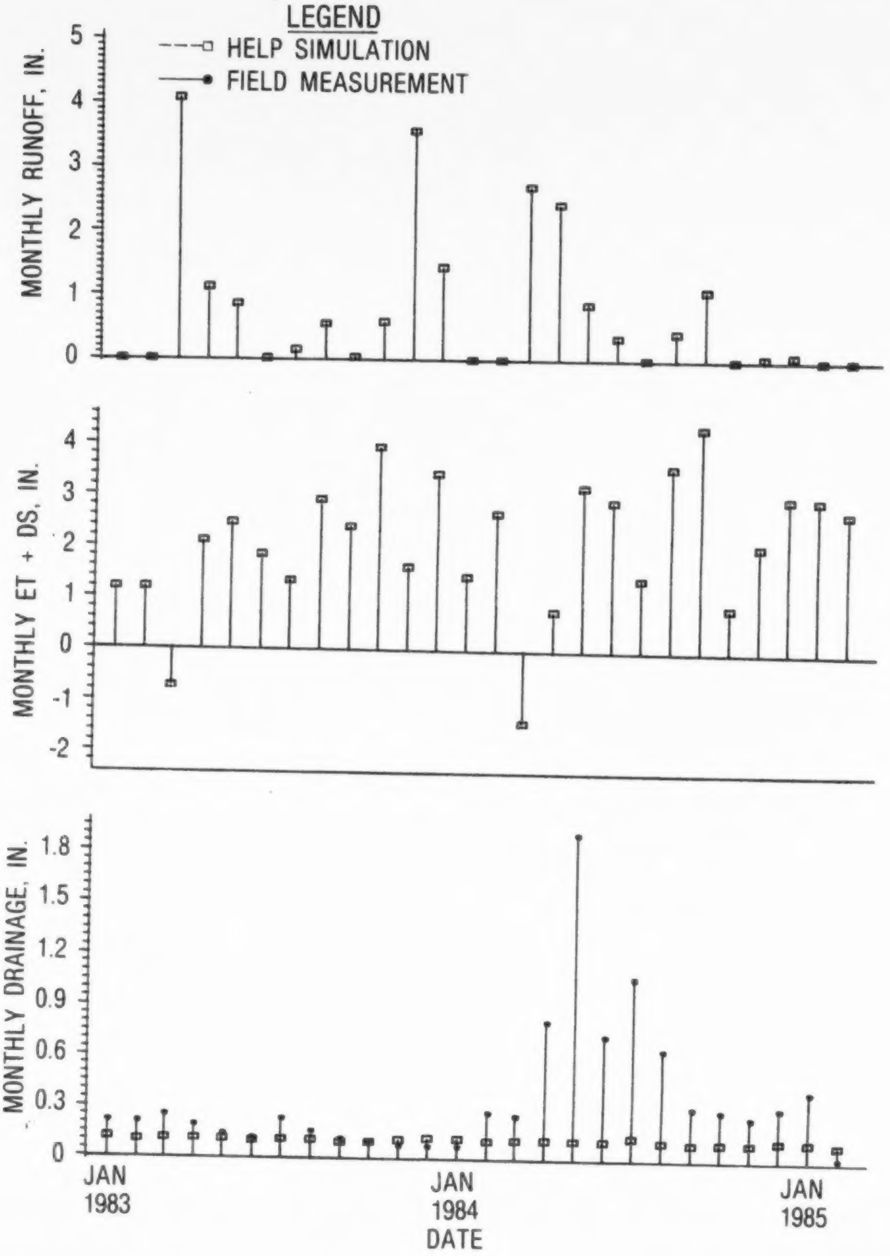

Figure 78. Field measurement of leachate drainage for Niagara Falls Cell 3 compared to HELP simulation; monthly comparisons.

SECTION 11

EVALUATION OF SIMULATIONS

Mathematical simulations of 20 landfill cells at seven sites across the United States were made, and the results were compared to measured field data. These landfills included a wide variety of conditions for which the HELP model was tested. This section summarizes the results of these simulations and evaluates the level of verification that has been accomplished.

EVALUATION OF FIELD DATA

It was found that the extent of available data on landfill leachate production is very limited, especially for periods of record which extend significantly beyond the initial water budget equilibration period, which may last up to several years. The extent of available data on other important facets of the water balance, such as runoff, evaporation, rainfall, soil moisture, leachate ponding depths, percolation rates, and detailed soil characteristics are even more limited. The scarcity of data is understandable since data collection can be costly. Nevertheless, the level of field verification of the HELP model and the resulting level of understanding of the important processes involved in leachate production and migration are highly dependent on obtaining this information.

For this study, runoff volumes were measured from 11 landfill cells at two locations--all were test cells with surface areas less than 0.1 acre. Evaporation was measured at one site, but was not documented sufficiently for inclusion in this study. Daily rainfall was measured at one site. Soil moisture, leachate ponding depths, and barrier soil percolation rates were not adequately or consistently measured in any of the landfill cells. Most sites had at least limited data on the hydraulic conductivity of the clay liner, although the testing methods and the applicability of the results varied widely. Data related to characteristics of the cover soils or to the extent of surface vegetation were generally lacking.

The lack of adequate site description and measured water budget components affected the verification study in two ways. First, the lack of descriptive landfill information required the frequent use of default values in the HELP model, which introduced additional uncertainty into the verification. Second, the lack of water balance outflow measurements limited the number of HELP outflow predictions that could be verified. These limitations restricted the ability of the study to isolate and test mathematical characterizations of specific physical processes, such as soil moisture storage and routing, evapotranspiration demand and its distribution through the soil profile, unsaturated vertical drainage, and details of the apportioning of leachate production between lateral drainage to collection systems and vertical percolation through the clay liner.

In addition, the variable degree of field measurement precision and reliability presented challenges in interpreting the data which did exist. None of the field data used in this report were collected specifically for verifying the HELP model; therefore, the field data were not always consistent with the needs of this study. For instance, the data available for the three largest landfills were collected while they were simultaneously undergoing expansion. In other cases, there was large variability in measured results between otherwise identical landfills. All of this required a significant amount of engineering judgment in interpreting the data for the HELP model comparisons.

Although a detailed verification of specific model components was not always possible, the data did confirm the model's overall utility in estimating a landfill water balance even without extensive knowledge of specific landfill characteristics. This was an important finding since the HELP model is typically used with a limited amount of detailed landfill information.

EVALUATION OF MODEL PREDICTIONS

Runoff

Measured runoff data existed for eight cells at the University of Wisconsin and for three cells at Sonoma County, CA. In all cases, an attempt was made to calibrate the runoff curve number in advance of the simulation by examining measured rainfall-runoff data. These calibrated curve numbers were used for the simulations, but they were consistent with default values that would have been selected by the HELP model based on surface vegetation and the minimum infiltration rate of the topsoil. Runoff was overpredicted for five cells by an average of 30 percent of the measured runoff, and underpredicted for six cells by an average of 20 percent of the measured runoff. Following these initial simulations, the curve numbers were varied to determine their effect on the overall model prediction of landfill performance. Five simulations were improved by a change in curve number--all had originally underpredicted runoff.

For the three cells at Sonoma County, it was obvious that the evapotranspiration and/or soil characteristics were controlling runoff volume and not the curve number. Because of this close interaction, it was difficult to assess the accuracy of the curve number method in the HELP model based on the field data in this report. However, the predicted runoff volumes appear overall to be in reasonable agreement with the measured results.

A comparison of measured and predicted runoff on a monthly basis for the University of Wisconsin cells indicated that the assumptions used in the HELP model for snowmelt runoff may not be appropriate. The model stores all precipitation on the surface when the mean daily temperature interpolated from the mean monthly temperature is below freezing. When this mean daily temperature rises above freezing, the precipitation is allowed to either run off or infiltrate. Since mean daily temperatures are computed in the HELP model based on mean monthly temperatures which are generally below freezing in Wisconsin for several consecutive months, no runoff was predicted by the HELP model during the winter. Instead, a large runoff volume was predicted during April of each year when temperatures warmed. This compared to measured results which showed significant runoff throughout the winter without an excessively large runoff in April. This discrepancy probably contributed to the overprediction of runoff for several cells.

It should be noted that the measured runoff data examined in this report were restricted to relatively flat surfaces. The effect of steeper slopes typical of mound construction was not specifically studied.

Evapotranspiration

No suitable evapotranspiration field data from landfill sites was found for model testing. This was not unexpected due to the complexities involved in collecting this type of data. Yet, evapotranspiration is typically the single largest outflow component of the landfill system; therefore, small changes in evapotranspiration can have major impacts on volumes of lateral drainage and barrier soil percolation.

Of particular importance and interest was the appropriate depth to assume for the evaporative zone in the top subprofile. As shown in the sensitivity analysis, an increase in evaporative depth from 4 to 18 inches can decrease leachate production by more than 50 percent. However, the simulations in this study were only able to indirectly assess the evaporative depth assumptions.

For those cells which had runoff data available, a surrogate variable for evapotranspiration was identified, and comparisons were made between measured and predicted results. The variable consisted of the sum of the water balance components which were not directly measured. In the case of the University of Wisconsin cells, the variable was the sum of evapotranspiration and change in moisture storage, ET+DS. For the Sonoma County cells, it was the sum of evapotranspiration, change in moisture storage, and percolation, ET+DS+PERC. The ET+DS variable was found to be underpredicted by an average of 4 percent of the measured values, whereas the ET+DS+PERC variable was underpredicted by an average of 25 percent. It is obviously rather complex to discern the meaning of these results since evapotranspiration, change in moisture storage, and percolation are all interrelated. The evidence suggests that values chosen for evaporative depths may have been too small. However, for the Sonoma County landfills, an increase in the evaporative depth from 4 to 24 inches had only a small effect on the ET+DS+PERC results.

Lateral Drainage and Percolation

Since measurements of barrier soil percolation volumes and leachate ponding depths were generally not available, the lateral drainage and barrier soil percolation submodel could only be evaluated using measured drainage data. One exception was the Boone County, KY, cell where barrier soil percolation volumes were measured. However, the configuration of the clay liner and percolation collection pipe was such that vertical percolation did not actually occur; rather, the percolation flow paths were forced to converge radially toward the collection pipe. The attempt to simulate this percolation using the HELP model resulted in an overprediction of approximately 35 percent.

Lateral drainage was overpredicted by 10 percent of the measured drainage in two cells where very high leachate collection rates were observed. In three cells where very small quantities of leachate were collected, lateral drainage was underestimated by 97 percent of the measured drainage, although this difference amounted to only 1.4 inches per year. Of the remaining nine cells, lateral drainage was overpredicted by an average of 4 percent of the measured drainage in five covered cells and overpredicted by an average of 53 percent of the measured drainage in four permanently uncovered cells with a weathered waste surface that supported dense vegetation. Small errors in the hydraulic conductivities of the cover soils can cause large differences in the leachate production when the leachate production is small. Also the overpredictions may have been partially related to the manner in which the HELP model estimates unsaturated hydraulic conductivities. To linearly relate unsaturated hydraulic conductivity to moisture content between field capacity and saturation tends to overpredict unsaturated hydraulic conductivity. Thus, moisture is routed more quickly through the evaporative zone, contributing to larger leachate volumes and lower evapotranspiration volumes.

The cells at Sonoma County provided two important tests of the lateral drainage and barrier soil percolation submodel. First, the three cells without liquid redistribution generated very small leachate volumes due to low summer rainfall, high evapotranspiration, and a clay cover soil. As discussed previously, the initial simulation significantly underpredicted lateral drainage under these conditions. Second, the cells that included the additional inflow to the waste layer provided a case where infiltration rates to the lateral drainage layer were very large and essentially known. Under these conditions, the submodel very closely reproduced measured lateral drainage volumes.

The poor reproductions of lateral drainage for three of the Sonoma County cells could have been influenced by two assumptions incorporated in the HELP model related to barrier soil percolation. First is the assumption of free outfall conditions below the clay liner. In many cases, the hydraulic conductivity of the underlying soils is indeed larger than that of the clay liner, and the assumption that the head at the base of the liner is zero during vertical flow may be reasonable. However, it is also possible that groundwater conditions beneath the clay liner, such as saturated soil layers under the liner, may increase this head and therefore reduce percolation rates. If such conditions are known from soil borings or monitoring wells, the thickness of the clay liner could be artificially adjusted in the HELP model to account for the increased resistance to percolation.

Secondly, the model assumes that the barrier soil layer is saturated for the purposes of vertical flow calculations. This would likely be the case after long-term operation of the landfill. However, the time period for the wetting front to move through a very thick, impermeable clay liner to create the saturated condition may be lengthy. During this period, the percolation rate will likely be reduced below that of the saturated hydraulic conductivity. Therefore, modeling the early life of landfills might require the use of a reduced hydraulic conductivity for barrier soil layers. There was insufficient information from the Sonoma County cells to test these two assumptions.

The cells at Niagara, NY, presented special problems for the purposes of HELP model verification. The cover included a synthetic liner that theoretically eliminated surface water infiltration into the cell. Yet significant leachate drainage was measured. Therefore, leakage into the cell must have occurred either from surface water through failed portions of the synthetic liner in the cover or from groundwater through the clay liner (and synthetic liner for Cell 1) on the sides and base. The modeling difficulty was twofold. First, there was no basis from field information for assigning a leakage fraction to the synthetic liner. Second, the HELP model does not have capability to simulate groundwater seepage into the cell. However, the analysis (for the first 15 months) did show that assigning a reasonable leakage fraction to a synthetic liner can reasonably reproduce measured lateral drainage volumes in a leaky landfill.

SECTION 12

SUMMARY AND CONCLUSIONS

Existing field data from landfill sites across the United States were evaluated for their suitability in verifying the HELP computer model. Seven sites were selected for analysis in this report. A total of 20 landfill cells were simulated, ranging in size from 0.04 to 24 acres. Simulation periods ranged from 2.5 to 8 years. Measurements of leachate drainage were available from all landfills, while data on runoff were available from about half of the landfills.

In most cases, daily rainfall and monthly temperature data were obtained from the nearest National Oceanic and Atmospheric Administration weather station for use in the model. Solar radiation values stored in the HELP model were used for all simulations.

Model input values were determined from published reports describing the construction and operation of each landfill. In general, little detailed information was available on soil characteristics, surface vegetation, runoff curve numbers, or evaporative depths, so that extensive use was made of default values stored in the HELP model.

The measured data used for comparison with the HELP model simulations were primarily lateral leachate drainage volumes. Measured runoff data were available from 11 landfill cells. Barrier soil percolation was measured at one landfill, although its suitability for model verification was limited. There was a high degree of variability in the data from similar landfill cells.

Where runoff data were available, an attempt was made to calibrate the runoff curve number in advance of the simulation by examining measured rainfall-runoff data. These calibrated curve numbers were used for the simulations, but they were consistent with default values that would have been selected by the HELP model based on surface vegetation and minimum infiltration rates. Runoff was overpredicted for five cells by an average of 30 percent and underpredicted for six cells by an average of 21 percent.

No suitable evapotranspiration field data from landfill sites were found for model testing. However, the results of this study raise the possibility that the evaporative depths suggested by the HELP model are too small.

Lateral drainage was overpredicted by 10 percent of the measured drainage in two cells where very high leachate collection rates were observed. In three cells where very small quantities of leachate were collected, lateral drainage was underestimated by 97 percent. Lateral drainage was overpredicted by an average of 4 percent in five covered cells and overpredicted by an average of 53 percent in four permanently uncovered cells. Percent deviations were not computed for the remaining cells due to the nature of their simulation analysis.

In addition to field verification, a sensitivity analysis of the HELP model was performed to examine the effects of the major design parameters on components of the water budget for landfills. The analysis examined the effects of cover design, topsoil thickness, topsoil characteristics, vegetation, runoff curve number, evaporative depth, drainable porosity, plant available water capacity, hydraulic conductivity, drainage length, and liner slope on the water budget. Hydraulic conductivity values for the topsoil, lateral drainage layers and clay liners are the most important parameters in determining the water budget components. These parameters are particularly important in estimating the percolation through the landfill. Other design parameters tend to affect the apportionment between runoff, evapotranspiration and lateral drainage from the cover.

The information from the sensitivity analysis and the verification results were used to evaluate RCRA landfill design guidance and regulation. This evaluation showed that saturated hydraulic conductivity is the most important design parameter for minimizing percolation. Care should be taken to recommend the highest hydraulic conductivity that is commonly available for drainage media. Similarly, the lowest saturated hydraulic conductivity practically obtainable should be used as guidance for soil liners. Changes in other design parameters yield much smaller effects on percolation if the values of these parameters are kept in a reasonable range.

The following conclusions are made. The field data verified the utility of the HELP model for estimating general landfill performance. However, not all model components were well tested due to the limited field data available. It is concluded that a laboratory and field monitoring program explicitly designed for HELP verification would be necessary for further refinement of specific model components. In addition, studies are needed to examine lateral drainage and percolation for small infiltration rates and flow through synthetic liners and in leakage detection of double liner systems.

The overall data base of long-term water budget measurements at landfills is poorly organized and too small to continually advance the state of the art in understanding landfill leachate generation and migration. More extensive monitoring activities are required to fill this gap.

The HELP model was shown to simulate particularly well the leachate drainage from landfills with relatively large infiltration rates. The model did not simulate well the leachate drainage due to very small infiltration rates, although this could have easily been due to the selection of values describing the cover characteristics. Runoff predictions were found to be within an average of plus or minus 25 percent of measured data. Evapotranspiration verification data were lacking and should be emphasized in future studies due to their significant impact on the overall water balance. In general, the error in estimates of water budget components were much smaller than the variability in the field measurements for similar landfill cells. These results are very good in light of the fact that the precipitation data used in this study, which is known to be spatially highly variable, were not measured at most of the landfill sites.

Improvement to the HELP model should be made in the areas of snowmelt, winter runoff, unsaturated hydraulic conductivities, and the selection of evaporative depths.

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